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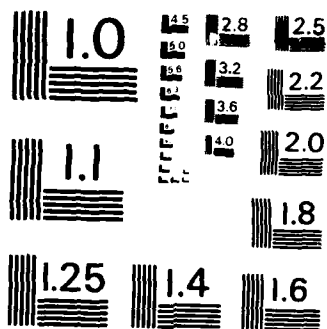   EXPERIMENT STATION VICKSBURG MS GEOTE..
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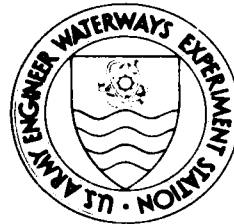
US Army Corps of Engineers

AD-A142 324

GEOPHYSICAL INVESTIGATIONS IN SUPPORT OF CLEARWATER DAM COMPREHENSIVE SEEPAGE ANALYSIS

by

Joseph P. Koester, Dwain K. Butler,
Stafford S. Cooper, and Jose L. Llopis

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May 1984

Final Report

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Prepared for U. S. Army Engineer District, Little Rock
Little Rock, Ark. 72203

84 06 2 037

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper GL-84-3	2. GOVT ACCESSION NO. AD-A142 324	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* GEOPHYSICAL INVESTIGATIONS IN SUPPORT OF CLEARWATER DAM COMPREHENSIVE SEEPAGE ANALYSIS		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR*(s)* Joseph P. Koester, Dwain K. Butler, Stafford S. Cooper, and Jose L. Llopis		8. CONTRACT OR GRANT NUMBER*(s)*
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Geotechnical Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Engineer District, Little Rock P. O. Box 867 Little Rock, Ark. 72203		12. REPORT DATE May 1984
		13. NUMBER OF PAGES 84
14. MONITORING AGENCY NAME & ADDRESS*(If different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285
Port Royal Road, Springfield, Va. 22161.

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*
Dams (LC)
Seepage (LC)
Geophysical research (LC)
Clearwater Dam (Missouri) (LC)

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
A series of surface geophysical investigations were conducted at Clearwater Dam, Missouri, to supplement a U. S. Army Engineer District, Little Rock, comprehensive seepage study. This report compiles the effects of two field exercises performed to delineate paths or zones of seepage through the left abutment materials. Procedural details and test results are presented for earth resistivity, spontaneous potential, and refraction seismic surveys, individually and collectively as appropriate to demonstrate the effectiveness of the methods in locating flowing water in subsurface materials at this site.

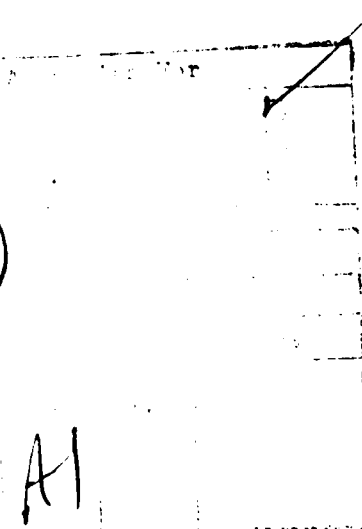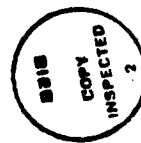DD *FORM 1473* EDITION OF 1 NOV 65 IS OBSOLETE

PREFACE

Geophysical investigations of seepage conditions at Clearwater Dam were authorized by the U. S. Army Engineer District, Little Rock, in IAO No. 81-142 dated 6 March 1981.

The field investigations were performed in two phases by personnel of the Earthquake Engineering and Geophysics Division (EE&GD), Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), during the periods 16-20 March 1981 by Messrs. Dwain K. Butler, Jose L. Llopis, Joseph P. Koester, and Thomas B. Kean II, EE&GD; and 26-29 May 1981 by Messrs. Koester and Stafford S. Cooper, EE&GD. Little Rock District geotechnical personnel, under the direction of Messrs. Johnny M. Browko and Steven G. Hartung and supervision of Mr. Charles M. Deaver, provided essential field implementation and assisted in all aspects of the operation.

The data analysis and report preparation for the March 1981 phase were performed by Messrs. Butler and Llopis, and for the May 1981 phase by Messrs. Cooper and Koester. Letter reports were submitted for each phase to the Little Rock District. This report was prepared by Messrs. Koester, Butler, Cooper, and Llopis, under the general supervision of Drs. A. G. Franklin, Chief, EE&GD, and W. F. Marcuson III, Chief, GL. Mr. Deaver submitted the Appendix to this report to provide an overall seepage data analysis and summary.

COL Tilford C. Creel, CE, was Commander and Director of WES during the performance of these investigations. Mr. Fred R. Brown was Technical Director.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
gallons	3.785412	cubic decimetres
miles	1.609347	kilometres
pounds (mass)	0.4535924	kilograms

GEOPHYSICAL INVESTIGATIONS IN SUPPORT OF

CLEARWATER DAM COMPREHENSIVE SEEPAGE

ANALYSIS

PART I: INTRODUCTION

1.   The U. S. Army Engineer District, Little Rock (LRD) conducted a comprehensive seepage analysis of Clearwater Dam, Mo., covering the period 1949 (when the dam was completed) to 1981. This report documents a series of surface geophysical investigations of the left (east) abutment, performed in two phases in the spring of 1981 to augment prior efforts by LRD in defining seepage zones or paths. The investigations were conducted by personnel of the Earthquake Engineering and Geophysics Division (EE&GD), Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES). The findings of these geophysical tests are included in the report of the LRD comprehensive study (U. S. Army Engineer District, Little Rock, 1981).

2.   Clearwater Dam is located in southeastern Missouri near Piedmont (Figure 1a). Seepage outlets have been observed in downstream left abutment areas (Figure 1b) when reservoir pool elevation exceeds 500 ft*; the last high pool occurrence (el 550.4 ft) occurred in May 1979. The LRD described the seepage as "unsightly both physically and psychologically" (U. S. Army Engineer District, Little Rock, 1979). A suggested test program involving seismic refraction and resistivity surveys was received from Mr. Charles Deaver, LRD. After review of the Clearwater Dam Foundation Completion Report (U. S. Army Engineer District, Little Rock, 1977) and the site map, a revised test program was planned with the concurrence of Mr. Deaver. The surveys were planned in two areas (Figure 1b): (a) in the downstream left abutment areas above suspected possible seepage paths; and (b) in the floodplain along downstream toe of dam to investigate an area where a piezometer boring encountered rock at 70 ft, about 40 ft deeper than the average depth to the top of rock for the area.

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*   A table of factors for converting U. S. customary to metric (SI) units of measurement is given on page 3.
    All elevations are referenced to mean sea level.

3. In early conversations with Mr. Deaver, the successful application of spontaneous potential (SP) measurements to locate and monitor seepage paths at Gathright Dam, Va., was described. Since there was no surface seepage occurring at Clearwater Dam at the time due to low reservoir pool levels, LRD attempted to induce seepage or alter the ground-water regime in the left abutment by pumping water into a piezometer boring on the crest of the dam. The pump test succeeded in inducing seepage at an upstream seep exit shown in Figures 1b and 2 and in raising water levels at piezometer locations by as much as 10 ft in downstream areas. Mr. Deaver requested that WES perform a limited SP feasibility study above the probable paths of flow to the upstream and downstream seepage during a second pump test which was to be conducted during the WES field work.

4. Part II of this report details the first of two operations conducted at Clearwater Dam, involving the seismic, resistivity, and SP feasibility studies of 16-20 March 1981 (Phase I). Part III documents a continuation of the SP investigation, warranted by findings of the March tests (Phase II). The Phase II operation was conducted during the period 26-29 May 1981. The appendix, provided at the time of publication by Mr. Deaver, describes how the WES studies completed the overall seepage analysis and gives the final interpretation of seepage conditions.

PART II: PHASE I - SEISMIC, SPONTANEOUS POTENTIAL, AND
RESISTIVITY STUDIES, 16-20 MARCH 1981

Purpose and Scope

5. The primary objectives of this field program were to (a) detect con-
ditions which might indicate seepage paths using resistivity and seismic re-
fraction methods, (b) determine depths to the top of rock in areas along the
downstream toe of the dam and base of the left abutment, and (c) assess the
feasibility of using SP techniques to detect and monitor seepage at the site.
A secondary objective was to brief and instruct District personnel in the use
and interpretation of the geophysical surveys and results.

Geophysical Surveys

6. The revised geophysical program planned for the site was reviewed
with Messrs. Steve Hartung and Johnny Browko, LRD, prior to beginning field
work. At their suggestion, the program was altered somewhat to better cover
areas of specific interest. Also it was decided to extend the SP feasibility
study to include an array in the downstream area below the site of the pump
test. Discussion of seismic refraction and resistivity field procedures and
interpretation methods will be cursory since the procedures used are somewhat
standard and are thoroughly discussed in geophysics texts (Telford et al.,
1976) and also in Engineer Manual 1110-1-1802 (Department of the Army, 1979).
Although the SP method is also discussed in various references, because it is
likely less familiar, field procedures will be discussed in more detail.

SP surveys

7. The location and layout of the two SP surveys are shown in Figure 2.
The basic objective of SP surveys is to detect potential differences (volt-
ages) on the surface generated by flowing (seeping) water in the subsurface.
The generation of SP by water flowing through soil and rock, as well as by
other sources, is reviewed in Telford et al. (1976) and Cooper, Koester, and
Franklin (1982). The field procedure consists of emplacing electrode arrays
in grid or profile patterns and measuring voltages between each of the elec-
trodes and a reference electrode. The reference electrode is placed far from
the arrays where the potential remains constant relative to the arrays.

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8. The electrodes for arrays SP-1 and SP-2 were 2-ft-long copper rods driven 1-1/2 ft into the ground at 50-ft spacings in both arrays. Array lengths for SP-1 and SP-2 were 700 and 500 ft, respectively. A 3-ft copper rod, driven 2-1/2 ft into the ground at the location indicated in Figure 2, was used for the reference electrode. The reference electrode was connected to the arrays by 18-gauge, multistrand copper wire, which was attached to 14-gauge solid copper wire laid out along the full length of each array with a takeout location provided for each electrode. SP measurements were then obtained by connecting the clip leads of a digital multimeter (50-megohm impedance) to a takeout on the solid copper reference wire and to an electrode. The ground, or negative clip lead, was always attached to the copper wire to maintain a standard polarity convention.

9. A complete set of SP measurements for both arrays required about 45 minutes, and measurements were made three times each day, at approximately 0900, 1300, and 1630. The first set of readings were obtained at 0900 on 17 March approximately 24 hr after installation of the electrodes. Pumping was initiated at 1445 on 17 March in boring LK-10 on the crest of the dam (Figure 2) and terminated at 1048 on 20 March. The pumping rate was 240 to 250 gpm, and 975,000 gal were pumped during the program. The final SP measurements were obtained at 1630 on 20 March. Depth to the water table was 119.9 ft in LK-10 prior to pumping. During pumping the ground-water level indicated in LK-10 was raised to a depth of 69.6 ft and remained nearly constant. After termination of pumping, the ground-water level in LK-10 fell to a depth of 88.7 ft by 1330 on 20 March (time of last reading). The reservoir water level was at 494 ft during this test.

Resistivity surveys

10. Locations of the resistivity surveys are indicated in Figures 3a and 3b. Three types of surveys were conducted: (a) vertical resistivity sounding (Wenner array); (b) horizontal resistivity profiling (Wenner array); and (c) pole-dipole profile sounding (Bristow array). These three types of resistivity surveys are described in detail in EM 1110-1-1802 (Department of the Army, 1979). Briefly, the Wenner array consists of two current and two potential electrodes along a line with spacing a between each electrode. In general, for a given a-spacing, the resistivity determination can be considered to be influenced by material shallower than depth a . Resistivity sounding involves expanding the Wenner array (i.e., successively increasing the

a-spacing) along a line about a surface point, and the interpretation procedure attempts to produce a vertical profile of the variation of resistivity with depth. Resistivity profiling involves moving the Wenner array along a profile line keeping constant a-spacing to produce a horizontal profile of resistivity variations.

11. The Bristow array consists of a current electrode, C_1 , and two potential electrodes, P_1 and P_2 , which are moved along a profile line, and a second current electrode, C_2 , which is placed a large tance from the closest point on the profile line (approximately 500 ft) For this survey C_1 was advanced along the profile line at 50-ft intervals. r each position of C_1 , P_1 and P_2 are moved at 10-ft intervals with a s.   , of 10 ft to a total distance of 150 ft on each side of C_1 . The objective of this pole-dipole survey is to detect and map the profile location and depth of resistivity anomalies (such as caused by limestone pinnacles; clay-filled pockets; grikes; air-, water-, or clay-filled solution cavities; and seepage "channels").

12. Details of the resistivity surveys are given in the following tabulation with reference to Figures 3a and 3b:

Survey No.	Survey Type	Comments
RP-1	Resistivity profile	a = 50 ft; profile length = 450 ft; measurement spacing = 25 ft
RP-2	Resistivity profile	a = 50 ft; profile length = 850 ft; measurement spacing = 25 ft
RP-3A	Resistivity profile	a = 100 ft; profile length = 600 ft; measurement spacing = 50 ft
RP-3B	Resistivity profile	a = 50 ft; profile length = 500 ft; measurement spacing = 25 ft
RP-4	Resistivity profile	a = 50 ft; profile length = 550 ft; measurement spacing = 25 ft
RS-1	Resistivity sounding	Maximum a = 130 ft
RS-2	Resistivity sounding	Maximum a = 150 ft
RS-3	Resistivity sounding	Maximum a = 180 ft
B-1	Pole-dipole (Bristow) survey	Profile length = 350 ft; current electrode station spacing = 50 ft; Maximum distance C_1 to P_2 = 150 ft; Distance P_1 to P_2 = 10 ft
WG-1	Wenner grid survey	Survey about SSD-47 on grid pattern; a = 50 ft

Seismic refraction surveys

13. Locations of the six seismic refraction survey lines are shown in Figures 4a and 4b. Details of the individual survey lines are given in the following tabulation with reference to Figures 4a and 4b:

Line No.	Total Spread Length, ft	Geophone Spacing, ft
S-1	375	15
S-2	375	15
S-3	375	15
S-4	230	10
S-5	375	15
S-6A, B	710*	10

* This total spread length was only partially covered with forward/reverse seismic profiles due to high seismic energy loss in the area and to high wind and vehicular traffic noise levels.

14. The surveys were conducted using two different seismograph setups: (a) two EG&G Geometrics ES-1210F, 12-channel seismographs coupled together to give a 24-channel system; and (b) an SIE RA-49R, 24-channel seismograph. Sources for the survey were varying amounts of Kinepak two-component explosive ranging from approximately 1/5 to 2 lb TNT equivalent. Shotholes ranged from 1 to 3 ft in depth and presented considerable difficulty in digging due to cobbles in the overburden. In the vicinity of line S-6, a considerable thickness of humus and tree roots made it virtually impossible to detect seismic signals above a high background noise level at distances greater than about 300 ft even using 2 lb of explosive.

15. The dual objective of determining depth of the top of rock as well as detecting top of rock irregularities and other solution features necessitated the use of relatively long lines (greater than 200 ft) and close geophone spacings (10 to 15 ft). These constraints on the refraction surveys, as well as the difficulty in placing shotholes and the relatively high noise levels on several days during the field program, slowed the progress of the refraction surveys, making them somewhat inefficient for this site.

Results

SP surveys

16. Two concepts or hypotheses determine the manner in which the SP data are presented and analyzed: (a) areas on the surface below which seepage or streaming is occurring should be relative negative voltage anomaly areas; and (b) changes such as induced by pumping which result in greater flows through subsurface areas or involve new regions in the subsurface flow should result in negative changes in voltage (potential difference) relative to the reference electrode. Thus, the SP data are examined in static profile, i.e., plots of SP values at a given time, and in terms of changes in SP values during pumping relative to an initial static profile (before pumping).

17. Upstream SP array. Data for the upstream SP array are given in Table 1 and plotted in Figure 5. Figure 6 presents static SP profiles recorded at several times. The static profiles define four relative negative regions: (a) at electrode 1, (b) centered at electrode 5, (c) centered between electrodes 10 and 11, and (d) centered between electrodes 13 and 14. Using the SP measurements at 0900 on 17 March (prior to initiation of pumping) as reference values, Figure 7 presents plots of cumulative change in SP values for three times during the pumping test. Three areas of negative SP change can be seen in Figure 7: (a) at SP electrodes 1 and 2, (b) at SP electrodes 11 and 12, and (c) at SP electrode 15 (although the reading on 20 March (0800) is not consistent with the two earlier values at 15). Significantly, these three areas of negative change during pumping coincide with or are adjacent to three of the four negative zones indicated in the before-pumping static profiles shown in Figure 6.

18. Downstream SP array. Data for the downstream SP array are given in Table 2 and plotted in Figure 8. Static profiles recorded at several times are shown in Figure 9. Three prominent relative negative regions are indicated in the static profiles: (a) at SP electrode 4, (b) at SP electrode 6, and (c) at SP electrode 8. Again, using as reference values the static profile at 0900 on 17 March, profiles of cumulative change in SP values are plotted in Figure 10. Three areas of significant negative SP changes during pumping can be seen: (a) centered at SP electrode 3, (b) centered at SP electrode 8, and (c) centered at SP electrode 10. In fact, the data indicate a broad zone from SP electrode 6 to electrode 11 (and possibly beyond) which

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becomes consistently more negative during pumping. The largest negative change (-63 mv) indicated at SP electrode 8 coincides with a relative negative in the before-pumping static profile.

19. Discussion. At boring M-15 (el 575 ft), near the upstream SP array, the top of rock is at a depth of 51 ft (approximately el 524 ft) and the water table at a depth of 90 ft (approximately el 485 ft); this is similar to conditions at LK-10, where the top of rock is at el 509 ft and water table is at el 497 ft (prior to pumping). Thus, upstream changes resulting from pumping (beneath the SP array) will likely occur entirely in rock and consist of increased flow in solution-widened joints or other solution features and/or of introduction of flow in features which previously were "dry." In the downstream area (beneath the SP array), this is not the case, however. At boring I-10 (approximately el 565 ft), the water table is at a depth of 78 ft (approximately el 487 ft), while the top of rock is at a depth of 94 ft (approximately el 471 ft). Thus, it is possible that downstream changes resulting from pumping involve increased flow in solution features in rock as well as increased flow in the overburden.

20. Two aspects of the data support the above possibilities: (a) the broad zone of negative SP change for the downstream array, and (b) the trend of the SP values after termination of pumping. In Figure 8, the SP values for all electrodes of the downstream array are seen to exhibit a positive change of about the same magnitude. This behavior suggests at least two possibilities: (a) the potential of the reference electrode has changed, or (b) the water table has been generally lowered (decrease of flow) in the overburden under the entire SP array. Consideration of the data for the upstream array seems to rule out the first possibility since the electrodes do not consistently show the same trend after termination of pumping; in fact, some even show a decrease or negative change.

21. It is worth noting that the negative SP changes at electrodes 11 and 12 of the upstream array are approximately on a line between LK-10 and the upstream seep exit. Also, the negative changes observed at electrodes 3 and 4 of the downstream array are approximately on a line from LK-10 and I-10. No reason exists, however, to expect that the flow from the pumping site would be along a direct route to the seep exit or to I-10.

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Resistivity surveys

22.   __Along upstream SP array.__   Figures 11a and 11b present the results of
the Wenner resistivity sounding RS-3, centered on upstream SP electrode 7.
Qualitatively, the sounding curve indicates a relatively thin, high-
resistivity surface zone, underlain by a relatively thick, low-resistivity
zone, and beneath that a high-resistivity zone.   The cumulative resistivity
plot indicates three and possibly four interfaces at depths of 5 (?), 11, 35,
and 70 ft.   Assuming these interfaces, a computer code was used to calculate
the resistivities shown in Figure 11c which satisfactorily fit the data (Fig-
ure 11c).   The interface at 35-ft depth agrees fairly well with the depth to
the top of rock predicted from that at boring M-15.   A horizontal resistivity
profile, RP-4, was conducted along the SP array using an a-spacing of 50 ft
(one objective being to detect variations in the interface at 35-ft depth,
such as changes in depth, rock type, and character of the interface and rock
immediately below it).   Results are shown in Figure 12.   From 0 to 350 ft,
along the profile line, the apparent resistivity is relatively constant
(400 to 500 ohm-ft).   From 350 to 550 ft, the resistivity increases with a
maximum apparently reached at 525 ft.   The peak at 525 ft (between SP elec-
trodes 11 and 12) coincides with the zone of change in SP values during
pumping noted in Figure 7.   Two possible explanations for the increase in
resistivity between 350 and 550 ft are (a) a decrease in depth to the top of
rock, and (b) the occurrence of air-filled solution features just below or at
the top of rock.

23.   __Along downstream SP array.__   Two horizontal resistivity profiles,
RP-3A and RP-3B, were conducted along the downstream SP array using a-spacings
of 100 and 50 ft, respectively (Figure 13).   The profile for a = 50 ft
exhibits almost cyclic variations in resistivity with prominent lows exhibited
at 25, 350, and 450 ft of the profile line.   Although the depth to the top of
rock is known to be highly variable in the left abutment area, based on bor-
ings LK-10 and I-10, the depth to rock beneath the downstream SP array is
expected to be in the 65- to 95-ft range.   Thus, the a = 50 ft profile
reflects variations in overburden conditions (type, density, and water
content).   The a = 100 ft profile should include effects due to variations
in depth to the top of rock and conditions immediately below the rock surface.
Resistivities for the a = 100 ft profile are generally lower, probably due
to including effects of saturated and partially saturated overburden materials

(water table at approximately 80-ft depth). A resistivity high on the a =
100 ft profile at 250 ft is likely due to a limestone pinnacle (note that it
is high even though overburden resistivity on the a = 50 ft profile indi-
cates a relative low at that location). Also, the a = 100 ft profile indi-
cates a resistivity low at 350 ft, the location of the prominent low in the
a = 50 ft profile. The fact that the lows at 350 ft reach nearly the same
values suggests a greater depth to the top of rock at this location (flanking
the high at 250 ft). Because of the water table elevation indications in I-10
and LK-10, locations such as 350 ft, as well as 100 ft and 550 ft, are suspect
locations for increased, localized ground-water flow during elevated ground-
water levels such as during the pumping tests. Significantly, locations 100
and 350 ft (SP electrodes 3 and 8 locations) correspond to peak negative SP
change during the pumping test (Figure 10).

    24. Downstream toe of dam. Results of horizontal resistivity profile
RP-2 are shown in Figure 14 and results of vertical resistivity sounding RS-1
are shown in Figures 15a and 15b. The sounding curve in Figure 15a indicates
the possibility of significant effects due to lateral resistivity variations
(variations not due to changes in conditions beneath the sounding location),
and indeed it was not possible to obtain a geologically reasonable model
(layer thicknesses and resistivities) to satisfy the data.   The interface
suggested by the cumulative resistivity plot in Figure 15b at 15 to 18 ft may
correspond to the water table and the interface at 88 ft may correspond to an
impermeable zone (tight, no significant solution activity) noted in U. S. Army
Engineer District, Little Rock (1977) at depths of about 70 ft in this area,
although any interface depths interpreted from Figure 15b must be viewed with
considerable reservation due to the preceding comments. The source of a
significant lateral variation which probably affected the sounding is indi-
cated in Figure 14, where a prominent resistivity high occurs between 200 and
300 ft of the profile line. This is superimposed on a broader high extending
from 100 to 550 ft. Except for boring SSD-47, which indicted a depth to the
top of rock at 70 ft, all borings along the profile line encountered rock at
an average depth of 30 ft with variations of only 2 to 3 ft. A large lime-
stone pinnacle could explain the high from 200 to 300 ft, although none of the
borings confirms this condition in the general area. The drop to lower resis-
tivity values from 25 to 75 ft is likely due to the significant amounts of
clay observed in G-47 and SSD-47 which were not seen in other borings (such as

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G-42 and G-38) and/or the greater depth to the top of rock. Likewise, the
drop to lower resistivity values which extend from 600 and 850 ft is probably
due to the significant amounts of clay observed in G-34 and RD-6. The small
resistivity low at 750 to 778 ft may be due to the new collector system.

25. Results of the Wenner grid survey, WG-1, are shown in Figure 16 in
the form of a contour plot. The results of WG-1 do not suggest that greater
depth to the top of rock or greater clay content is present at SSD-47. The
data indicate a closed negative anomaly feature centered 25 ft toward the
right abutment from SSD-47. This negative feature could reflect increased
depth to rock and/or greater clay content. SSD-47 may have encountered a
vertical pipe or narrow, clay-filled fissure which would not have affected the
resistivity with a = 50 ft. A measurement at SSD-47 with a = 80 ft indi-
cated an apparent resistivity of ρ_a = 1670 ohm-ft, consistent with incorporat-
ing greater volumes of rock in the measurement and very close to the value at
the RS-1 sounding location for a = 80 ft.

26. <u>Base of left abutment ridge.</u> The results of horizontal resistivity
profile RP-1 are given in Figure 17. From 0 to 200 ft is a low resistivity
zone, consistent with the significant amounts of clay indicated in borings
C-26, D-26, E-27, and EF-27. For these borings, depth to the top of rock is
about 22 ft and depth to the water table is 18 to 20 ft (prior to pumping). A
prominent rise in resistivity from 200 to 300 ft is apparently due to a
decrease in depth to the top of rock from 21.6 ft at EF-27 to 12.6 ft at F-28.
A small anomaly occurs at 350 ft, followed by a general decrease in resistiv-
ity beginning at 500 ft, which probably reflects an increase in depth to the
top of rock between CF-29 (14.1 ft) and RD-6 (24 ft). The borings are close
enough to fairly well define conditions along this line and the resistivity
results are just consistent with the known conditions; although, if additional
borings are planned in this area, prospective locations are at 25, 350, and
within the zone from 150 to 200 ft.

27. <u>Crest of left abutment ridge.</u> Borings on the crest of the first
left abutment ridge in the vicinity of resistivity survey locations B-1 and
RS-2 indicate the top of rock at depths from 55 to 62 ft and the water table
at depths from 78 to 90 ft. Results of resistivity sounding RS-2 are shown in
Figure 18. The sounding curve shows possible effects of lateral variations in
resistivity for small a-spacings (less than 30 ft). An anomaly indicated for
a-spacings from 80 to 100 ft may be due either to subsurface conditions

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beneath the sounding location or again due to lateral variations. A possible subsurface model which fits the data reasonably well is shown in Figure 18, although the model does not match the known geology beneath the sounding location very well. The sounding curve was used to provide qualitative guidance for interpreting the pole-dipole survey. Figure 19 shows results of the pole-dipole survey (B-1). The data were analyzed to locate high and low resistivity anomalies, and Figure 19 shows the locations in section view of the interpreted anomalies. Numbers in the legend indicate the number of intersections which define the anomaly and thus reflect the degree of confidence placed on the existence of the anomaly and its location. Of particular interest is the set of anomalous conditions which exist apparently just above and below the water table beneath the profile location marked with the downward arrow (between 60 and 65 ft). A possible interpretation of the anomalies at this location is a large partially air-filled and partially water- or clay-filled solution feature passing beneath the profile line; i.e., the high anomaly could be an air-filled portion of the feature while the underlying low anomaly could be an air- or clay-filled portion. The proximity of this anomalous zone to areas of seepage during high pool suggests placement of an exploratory boring to a depth of about 150 ft at this location. Placement of an exploratory boring at profile location 125 ft should be considered as a second priority to investigate the cause of a low anomaly at the top of rock and a high anomaly at the top of the water table at this location. Note that the existence of the large low-resistivity anomaly centered below profile position 185 ft is partially confirmed by boring G-23 which encountered a 3-ft-thick, clay-filled cavity at depths of 66 to 69 ft.

Seismic refraction surveys

28. Results of the seismic refraction surveys are presented in Figures 20 to 26. The seismograph records were analyzed to determine the time of first arrival of a seismic event at each geophone location, and then the arrival time versus distance plots prepared. Straight-line segments were fit to the data and analyzed using standard procedures (Redpath, 1973; Telford et al., 1976) to yield seismic velocities and depths to interfaces between materials with different velocities.

29. **Downstream toe of the dam.** Seismic refraction lines S-1, S-2, and S-3 indicate two velocities along the profile line which average 1,350 and 12,700 fps. These velocities correspond to overburden material and bedrock

velocities, respectively. The average depth to the interface between these two materials, obtained by a straightforward interpretation of the data, is 25 ft. Figure 27 shows the computed depths to the interface along with known depths to the water table and top of rock. Note that the interpreted depths from refraction data are between the water table and top of rock depths. Apparently, the saturated overburden zone (between the water table depth and the top of rock) is a blind zone, i.e., a zone not thick enough to show up as a first-arrival seismic event. Such blind zones are a possibility when there is a large contrast between two indicated velocities on a seismic record. It is possible to estimate the maximum thickness of the blind zone using procedures suggested by Redpath (1973). Because the blind zone is a zone of saturated overburden material, it can be assumed to have a seismic velocity of about 5000 fps. With this assumption and using the average depth of 25 ft from the refraction analysis, the blind zone can have a <u>maximum</u> thickness of 16 ft, and the upper layer (unsaturated overburden materials) can have a minimum thickness of 21 ft. The combined thickness of the upper two layers, the depth of the top of rock, should then be in the range of 25 to 37 ft, which is in substantial agreement with known conditions. However, the presence of the blind zone prevents the use of the refraction results for continuous profiling of depth to the top of rock along the line.

30. <u>Base of left abutment ridge.</u> Results of seismic refraction line S-4 (Figure 23) indicate a substantial refraction anomaly in the vicinity of boring F-28. The refraction data indicate depth to the top of rock of 25 ft (on the end of the line near E-27) and 15 ft (on the end of the line near RD-6 and GF-29), which are in very good agreement with boring data. Figure 28 is a cross section along the refraction data. The anomaly in the refraction data between 80 and 160 ft is seen to be due to an abrupt change in depth to the top of rock. A 4000-fps material is indicated in the refraction data from shotpoint 1 near E-27 and correlates with a layer of sandy clay in the E-27 boring log. This sandy clay layer either pinches out or is too thin to be detected in the refraction data from shotpoint 2.

31. <u>Crest of left abutment ridge.</u> The refraction data for line S-5 (Figure 24) indicate considerable variation in overburden velocity from 2500 fps at the end farthest from the dam and 3350 fps closest to the dam. The top of rock is indicated at about 68 ft, which is in fairly good agreement with known depths. Seismic velocity in the rock is lower than encountered

with lines R-1 through R-4. The data from shotpoint 1 indicate an intermediate velocity zone with top at 32 ft and velocity 5200 fps; this depth corresponds closely to the top of a gravel-cobble zone and also the depth at which water was lost in drilling in borings C-23, D-23, E-23, F-23, and G-23. The gravel-cobble zone is not noted in boring J-23. The 5200-fps zone may be missing or too thin to be detected from shotpoint 2 or may have been missed due to poor data quality in the 60- to 200-ft range of profile locations.

32. Along downstream SP array. Refraction line S-6A (Figure 4b) used shotpoints 1 and 2 to obtain data with geophone spreads I and II (Figure 26). Refraction line S-6B used shotpoints 3 and 4 to obtain data with geophone spread II (Figure 27). Three velocity layers are encountered: (a) a thin surface layer 4 ft thick with velocity ranging from about 1200 to 1550 fps; (b) a second layer about 100 ft thick with a velocity of 4000 fps; and (c) rock at an interpreted depth of 103 to 111 ft with a velocity of about 19,000 fps. The first velocity layer correlates to the highly organic layer of leaves, roots, and soil with a thickness of 3 to 6 ft in the area. The second velocity layer probably corresponds to the thick gravelly clay layer noted in borings I-10. The high rock velocity correlates to the massive, hard dolomite encountered at a depth of 94 ft in boring I-10. Data from shotpoint 1 indicate considerable irregularity in the top or rock in the vicinities of profile positions 350 and 500 ft. The refraction time anomaly at the 350-ft location corresponds to a decrease in depth to the top of rock of about 16 ft, indicating a depth of about 95 ft at the location, which is in good agreement with the depth at boring I-10. Refraction time anomalies in the vicinity of the 500-ft profile location indicate decreases in depth to the top of rock of 25 to 30 ft. The preconstruction boring cross section along the dam center line indicated similar or even larger variations in depth to the top of rock.

33. Summary table of seismic velocities. The tabulation below summarizes the seismic velocities encountered during the refraciton surveys:

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	Seismic Velocities, fps		
Refraction Line No.	V_1	V_2	V_3
S-1*	1450	12,500	
S-2*	1350	12,600	
S-3*	1200	12,850	
Average	1350	12,700	
S-4	1350	4,000**	11,400
S-5	2900	5,200**	9,300
S-6	1350	4,000	19,000

*   Possible blind zone with velocity of about 5000 fps.
** Not seen in both forward and reverse profile
    directions.

At least three distinct rock velocities are evident. Rock velocities for
lines S-1 through S-3 are consistent and the rock velocity for S-4 is close in
vlaue to those from S-7 through S-3 (probably corresponding to Potosi forma-
tion dolomites). Line S-5 has a lower rock velocity which may correspond to a
different formation (Eminence formation dolomites) or to a more extensively
weathered rock or both. The 19,000-fps rock velocity for line S-6 clearly
represents a different type or condition or rock than encountered beneath the
other seismic lines; this velocity is surprisingly high and normally would be
indicative of a massive, dense, unweathered dolomite or limestone.

Recommendations

34. Results of measurements along two SP arrays, one upstream and one
downstream of a borehole used for a pumping test, indicated two types of
anomalies which support the feasibility of using SP measurements to aid in the
analysis of seepage conditions at this site: (a) the existence of static SP
anomalies which grow in magnitude during pumping. It is recommended that an
SP grid array be considered on the two left abutment ridges adjacent to the
downstream side of the dam to aid in defining seepage paths during the next
high pool level. The grid array of electrodes could be installed quickly at
first indications of imminent high pool levels.

35. A pole-dipole resistivity survey on the first left abutment ridge crest (Figure 3b, line B-1) indicates conditions possibly representing a significant solution feature. This feature is interpreted to be partially water- or clay-filled. A recommended drilling location is indicated in Figure 19, and it is suggested that the borehole be extended to a nominal depth of 150 ft.* It is possible that this feature, if proven by drilling to exist, could provide a seepage path for significant amounts of the surface seepage observed during high pool levels on the side and at the base of the ridge. Other anomalies indicated in the geophysical survey results are shown in the figures and described in the text.

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* As of August 1983, several piezometers have been installed in overburden materials in this area, but none to depths greater than 65 feet (personal communication, Mr. Steven Hartung, LRD, 15 August 1983).

PART III: PHASE II - EXTENDED SPONTANEOUS POTENTIAL STUDY,
26-29 MAY 1981

Purpose and Scope

36. The intent of the extended SP survey described herein was to pro-
vide a more selective and detailed coverage of the left abutment, but more
importantly to detect seepage flows induced by a higher reservoir level (>el
520 ft). The decision to extend the SP survey was based on both the encourag-
ing results obtained in the Phase I (feasibility) investigation (seepage was
induced by pumping during low reservoir, at el 494 ft) and because of more
favorable results anticipated from "natural" seepage caused by higher reser-
voir levels from 26-29 May 1981. (Seepage historically increased at Clear-
water Dam during headwater pools over el 510 ft.) Electrode arrays emplaced
during the Phase II study period were monitored by LRD personnel on several
occasions after WES personnel conducted their field visit. All data obtained
to 29 June 1981 are included.

37. Survey lines were selected to: (a) intercept possible downstream
seepage paths through the left abutment and contiguous areas of the dam; and
(b) extend the original SP arrays so that comparisons could be made with
results obtained in the earlier investigation. The extended electrode arrays
were emplaced by personnel of the LRD using the same procedures adopted for
the earlier work, and because of (b) above the original emplaced reference
electrode was also used for this study.

Spontaneous-Potential Surveys

38. Operational decisions were made in conference with Messrs. Charles
Deaver, John Browko, and Steve Hartung of the LRD, at various stages of the
study. In initial planning, it was decided to extend the original upstream
and downstream SP arrays as shown in Figure 29. This provided approximately
3200 ft of total survey coverage using two approximately parallel arrays. In
addition, extension survey line 2A, perpendicular to the downstream electrode
array, was located as shown in Figure 29. Wiring of the various electrode
arrays was completed the morning of 27 May, and data acquisition began immedi-
ately thereafter.

Results

39. Results from SP survey lines 1, 2, and 2A are shown in Figures 30-
32, respectively. The data obtained through 27 May were used to make a pre-
liminary interpretation of results that same evening. The rationale for
interpretation was that zones of negative SP values indicate probable paths of
seepage in the downstream direction, and that the negative magnitude of an
anomaly is in some way related to the quantity of flow; i.e., high magnitude
negative anomalies are taken to indicate greater flows than smaller magnitude
anomalies. This interpretation is shown in Figure 33, and the probable paths
of seepage are indicated as broad dashed arrows. Positive SP values are taken
to indicate either no seepage flow or flow toward the reference electrode (the
latter possibility is much less likely, and even if so, is of little consequ-
ence in this study).

40. The plan view of probable seepage paths shown in Figure 33 was used
as a basis for deciding that an additional downstream survey line should be
installed as shown in Figure 29. This survey line, designated 2B, was instal-
led the afternoon of 28 May and readings obtained are plotted in Figure 34.
As can be seen in Figure 35, the zones of pronounced negative anomalies from
line 2B correspond very closely with the seepage paths predicted on 27 May,
and thus serve to validate the interpretation given.

41. Figure 36 profiles the SP readings for the electrodes which were in
place during the feasibility survey of 16-20 March, superimposed with the SP
readings from 26 May for those electrodes. It can be seen from Figure 36a
that there are some significant variations between the static SP values
recorded 16-20 March for the 15 electrodes originally installed and the values
recorded on 26 May. In general, the May SP readings indicate a pronounced
positive shift in the data so that electrodes 1-9 all had positive values of
SP with respect to the reference electrode. The negative readings were also
reduced in magnitude with the exception of electrode 14. The reasons for this
inconsistent behavior are unclear, but the shift is probably the result of
changes in the ground-water flow regime induced by the rise in reservoir level
(+26 ft) since the original investigation. Greater coverage of the behavior
of SP readings with varied reservoir level was afforded by monitoring the
entire array of 26-29 May throughout the programmed reservoir sta ? lowering
by LRD, to be discussed in more detail later.

42. Figure 36b shows that the March and May downstream SP results correlate very well in general trends, but the May SP values along seepage paths exhibit a general negative shift ranging from -50 to -100 mv. This behavior is consistent with a greater seepage flow in the downstream direction which is known to occur during periods of high reservoir pool levels.

43. It is also interesting to compare SP results in the May investigation with Bristow-Bates resistivity data obtained during the Phase I study along the left abutment ridge nearest the river and perpendicular to the dam. These data are not reproduced herein but do indicate relative low resistivity zones 20 to 50 ft upstream of piezometer F-23 at a depth of about 60 ft, and approximately 30 ft downstream of F-23 at depths of 25 and 75 ft, respectively. Similar zones of low resistivity were indicated, but with less confidence, in the vicinity of piezometer G-23. The plan view of SP results (Figure 35) shows the good correlation of SP and resistivity results assuming that regions of low resistivity indicate probable zones of seepage. For the existing site conditions, this is a reasonable interpretation.

44. LRD personnel monitored the SP electrode arrays on several occasions at various reservoir stages after the visit by WES. LRD used a high-impedance (50-megohm) digital multimeter on loan from WES to measure the SP voltages by the following schedule:

> 18 June 1981 - reservoir stage, el 509.5 ft
>
> 19 June 1981 - reservoir stage, el 508.1 ft
>
> 29 June 1981 - reservoir stage, el 502.3 ft

The SP readings were taken for all of the array electrodes emplaced for the survey of 26-29 May and were communicated to WES for incorporation into the data analysis. All array electrode voltages were determined with respect to the same reference electrode as for the May study. Figures 37-40 are profiles of all SP data available through 1 July 1981, for the electrode arrays emplaced during the May investigation at Clearwater Dam.

45. SP readings for the upstream electrode array (array 1) are presented in Figure 37. The trend of the SP data for 18, 19, and 29 June is similar to the data recorded on 27 and 29 May, but maximum SP amplitudes in June are much reduced. A baseline, or average SP value for the upstream array, appears to be around 50-mv DC positive. Deviations from this baseline are anywhere from 50 to 150 mv less for the June readings than for May. This reduction in SP magnitude is consistent with the decline in reservoir stage from May to June

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(-17 to -24 ft from 18 to 29 June, respectively), and is taken to represent a concomitant reduction in seepage flow through the left abutment. There may also be some effect from changes in the ground-water condition in the vicinity of the reference electrode; i.e., the reference electrode may have become more positive in potential as the reservoir level dropped.

46. Figure 38 is a profile of the SP data recorded for the downstream array (array 2), located on the left abutment. Again, the general trend of variations is similar for the May and June readings, and the June readings also exhibit a reduction in deviations from a baseline value (in this case, the zero potential line). Interestingly, several electrodes, notably electrodes 15, 22, and 23, exhibit a much greater positive SP change than do others and electrodes 15, 18, and 22 exhibit a larger-than-average change in SP from 18 and 19 June to 29 June. These variations are consistent with the interpretation that seepage features, presumed to drive the SP in the negative direction when water is flowing through them, apparently had reduced flow at reservoir stages reached between 19 and 29 June.

47. Eleven electrodes were emplaced perpendicular to array 2, along a line formed by piezometers D-23, E-23, F-23, and G-23. Figure 39 shows that the largest changes in SP for this array (array 2A) were recorded for electrodes 3 and 9. The stability of the SP data taken from 18 June to 29 June, during continued reservoir drop, suggests that the seepage features had greatly reduced flow rates after the reservoir level dropped below el 510 ft.

48. Figure 40 shows the results of the monitoring of auxiliary array 2B, along the line formed by piezometers KJ-25, G-20, and E-15. The same reduction of negative SP anomalies with decreasing reservoir stage is seen as for arrays 1, 2, and 2A. Confidence in the interpretation that seepage paths have been detected at electrode 4 and 6 is reinforced by the large decrease in negative SP anomalies between May and June, as the reservoir level dropped. The involvement of these seepage features was apparently terminated between 29 May and 18 June.

Conclusions

49. SP results obtained in the Phase II studies appear to be in generally good agreement with results obtained in the Phase I geophysical investigation. Results of this SP study also appear to correlate well with the

information available from borings and conclusions drawn from other geologic information. The probable seepage paths shown in this report are considered to indicate general trends rather than specific feature dimensions. Therefore, SP results should be used with caution pending verification by borings or other truth information.

50. SP measurements made in this study were both stable and repeatable during each measurement interval. The long-term (over a period of weeks) variation in SP levels seems to correlate well with what has already been determined for seepage conditions in the left abutment; i.e., seepage occurs when the reservoir pool rises above el 510 ft. It appears that when proper precautions are taken to emplace the electrodes, and to minimize disturbance after they are seated 1-1/2 to 2 ft in the soil, then monitoring over a period of months or longer may prove feasible.

51. Results obtained in this study appear to confirm that negative SP anomalies, recorded when the reference electrode is located upstream from the seepage area, indicate zones of seepage and that the magnitude of the anomaly is related to the quantity of flow. The predictable behavior of the SP anomalies detected in this study cannot be attributed to topographic or material property variations, but appears to be governed instead by seepage conditions as influenced by reservoir levels.

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Table 1

SP Measurements (in Millivolts), Upstream Array

	Spontaneous Potential, Millivolts D.C.									
Electrode No.	17 March 0900 hrs	17 March 1600 hrs	18 March 0800 hrs	18 March 1300 hrs	18 March 1630 hrs	19 March 0830 hrs	19 March 1300 hrs	19 March 1630 hrs	20 March 0800 hrs	20 March 1600 hrs
1	-100	-104	-100	-115	-118	-112	-129	-130	-125	-126
2	+66	+62	+57	+48	+44	+44	+31	+30	+35	+41
3	+170	+178	+195	+198	+201	+212	+210	+214	+219	+240
4	+161	+160	+184	+179	+182	+176	+180	+182	+178	+205
5	-134	-62	-82	-89	-87	-97	-98	-97	-104	-72
6	+160	+169	+172	+172	+174	+172	+171	+176	+174	+196
7	+174	+182	+192	+196	+200	+202	+205	+208	+206	+234
8	+142	+142	+162	+157	+156	+164	+157	+156	+164	+180
9	+109	+135	+127	+128	+130	+119	+122	+125	+188	+146
10	-139	-148	-124	-148	-150	-132	-157	-155	-139	-143
11	-166	-175	-168	-175	-175	-174	-182	-182	-179	-164
12	-2	-10	-19	-24	-28	-30	-40	-40	-37	-23
13	-205	-201	-182	-194	-197	-181	-198	-196	-180	-177
14	-197	-204	-187	-197	-201	-186	-197	-197	-182	-172
15	-121	-160	-117	-146	-156	-127	-154	-160	-132	-144

Table 2

SP Measurements (in Millivolts), Downstream Array

Electrode No.	Spontaneous Potential, Millivolts D.C.									
	17 March 0930 hrs	17 March 1530 hrs	18 March 0845 hrs	18 March 1330 hrs	18 March 1645 hrs	19 March 0900 hrs	19 March 1330 hrs	19 March 1645 hrs	20 March 0830 hrs	20 March 1630 hrs
1	+203	+210	+209	+219	+220	+222	+226	+225	+228	+262
2	+187	+190	+197	+206	+207	+212	+216	+215	+219	+254
3	+143	+138	+129	+127	+128	+125	+121	+122	+121	+147
4	-75	-76	-39	-79	-81	-87	-92	-89	-85	-61
5	+117	+140	+166	+159	+155	+149	+149	+150	+147	+178
6	-124	-111	-125	-134	-135	-142	-149	-144	-148	-120
7	+155	+155	+134	+138	+136	+126	+126	+128	+120	+151
8	+35	+25	-7	-8	-10	-20	-23	-21	-28	-1
9	+120	+122	+116	+111	+110	+110	+103	+104	+107	+132
10	+117	+121	+87	+94	+92	+80	+80	+82	+72	+108
11	+74	+75	+58	+59	+57	+50	+50	+52	+48	+81
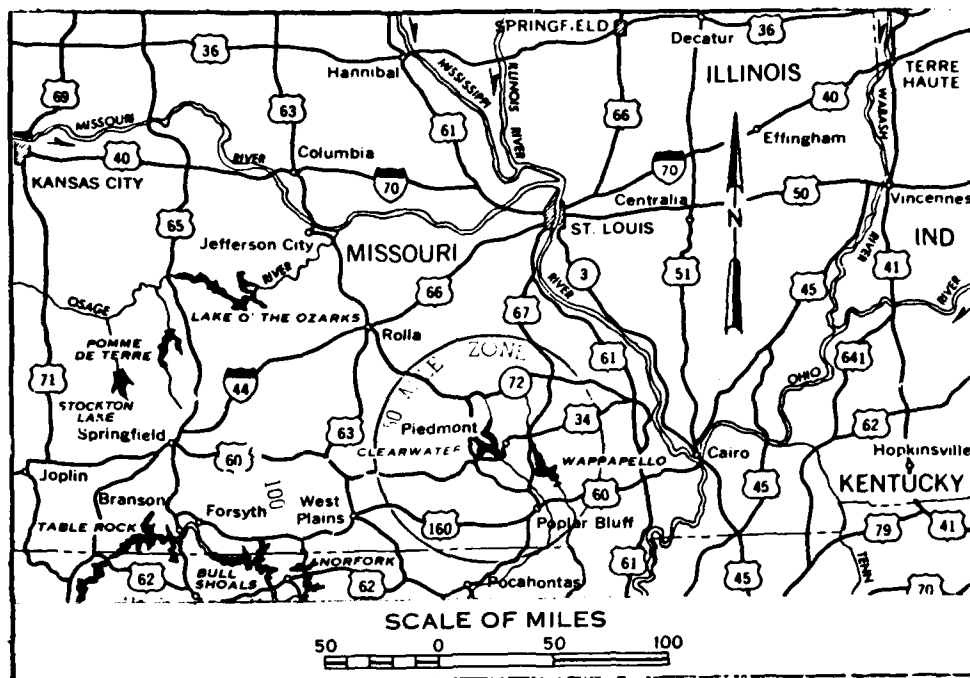
Figure 1a. Location map
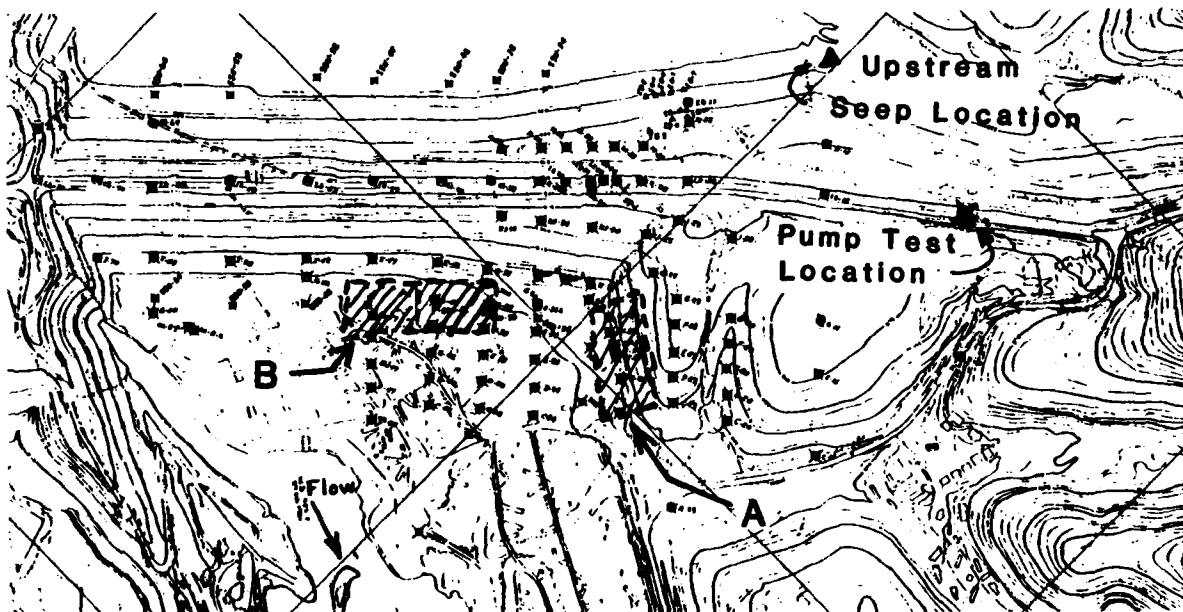
Figure 1b. Site map with test area locations:
A--left abutment seepage area;
B--top of rock investigation area.

Figure 1. Location and site maps, Clearwater
Dam, Missouri.
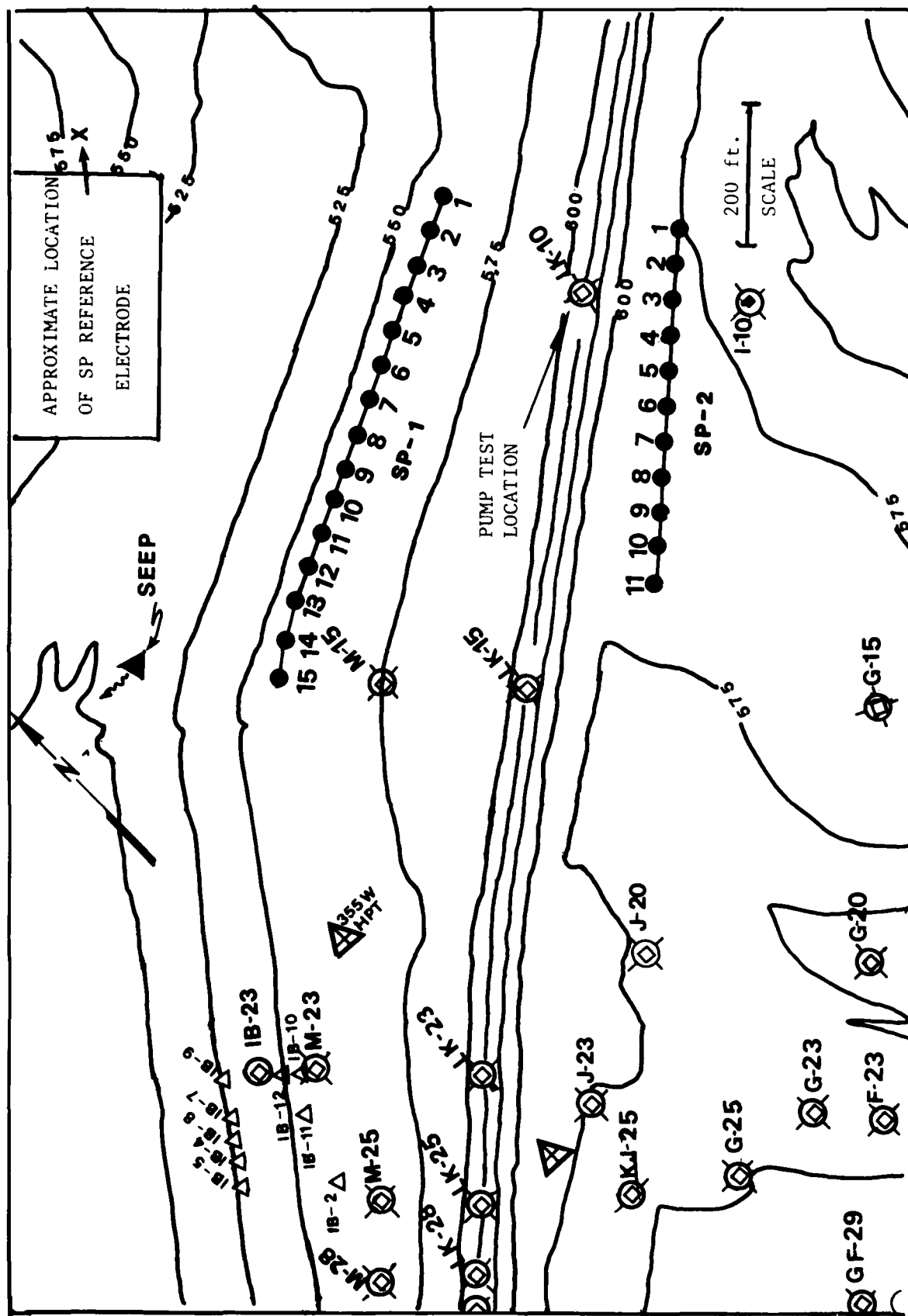
Figure 2. SP array locations
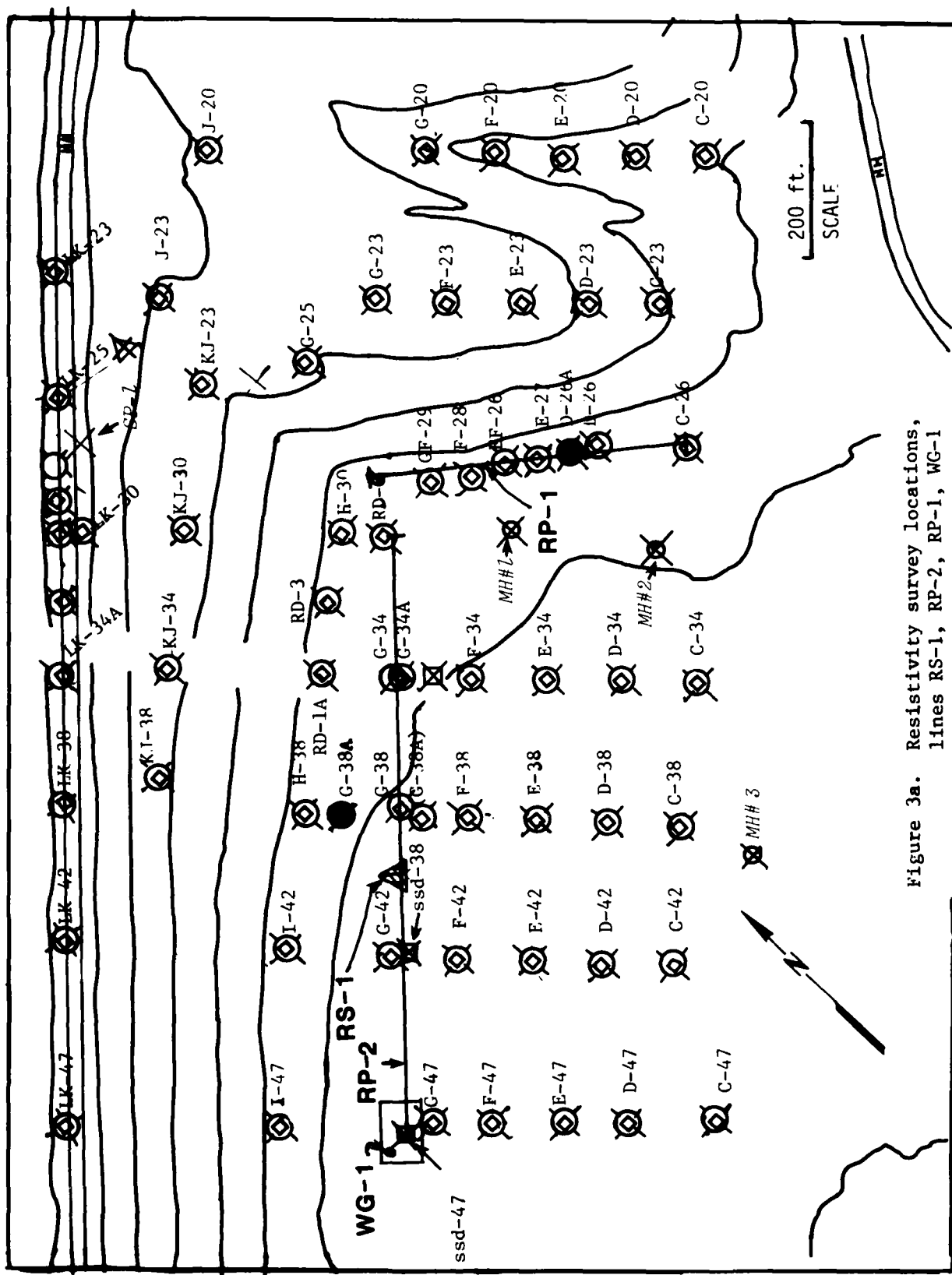
Figure 3a. Resistivity survey locations, lines RS-1, RP-2, RP-1, WG-1
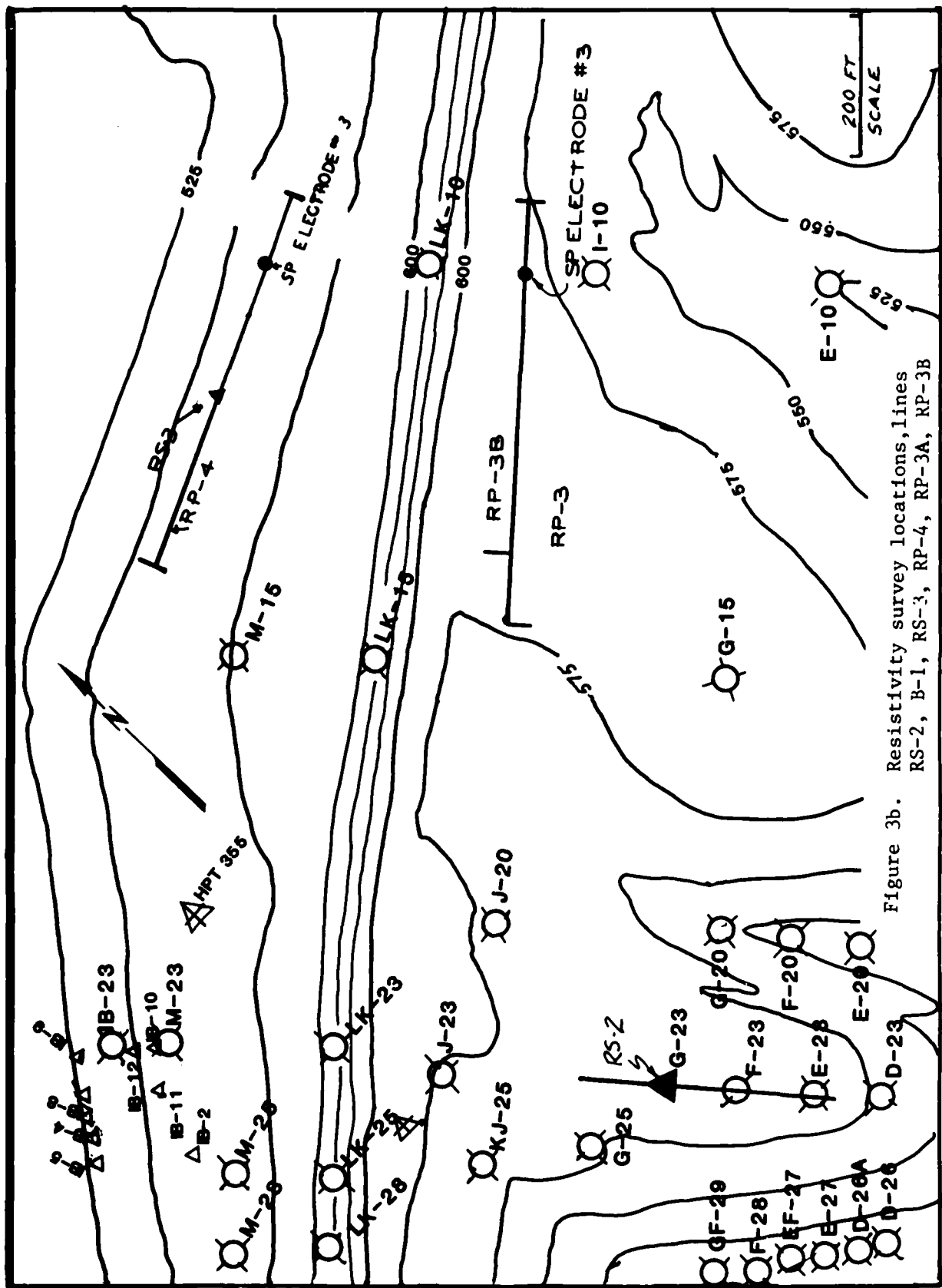
Figure 3b. Resistivity survey locations, lines RS-2, B-1, RS-3, RP-4, RP-3A, RP-3B
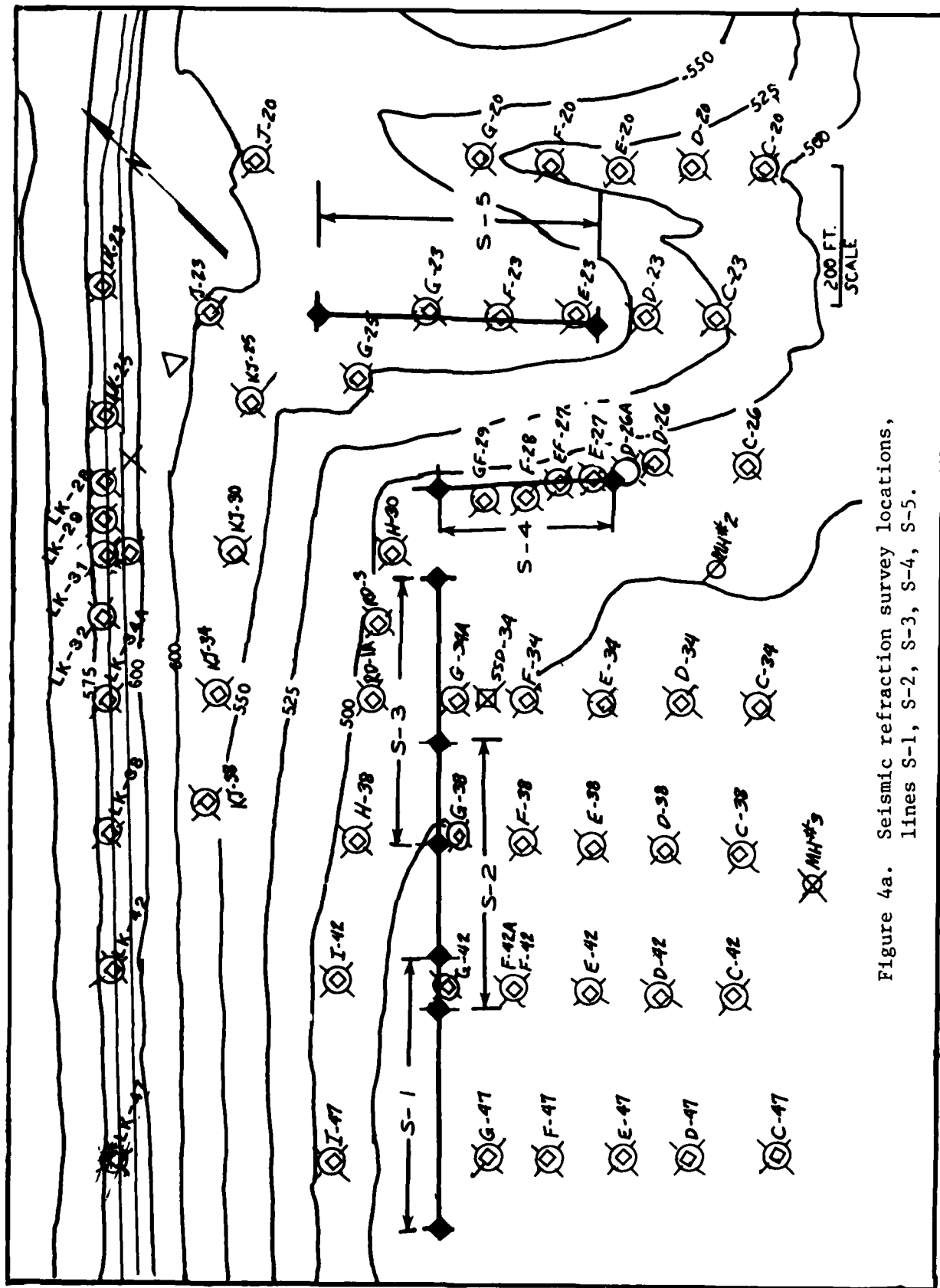
Figure 4a. Seismic refraction survey locations,
lines S-1, S-2, S-3, S-4, S-5.
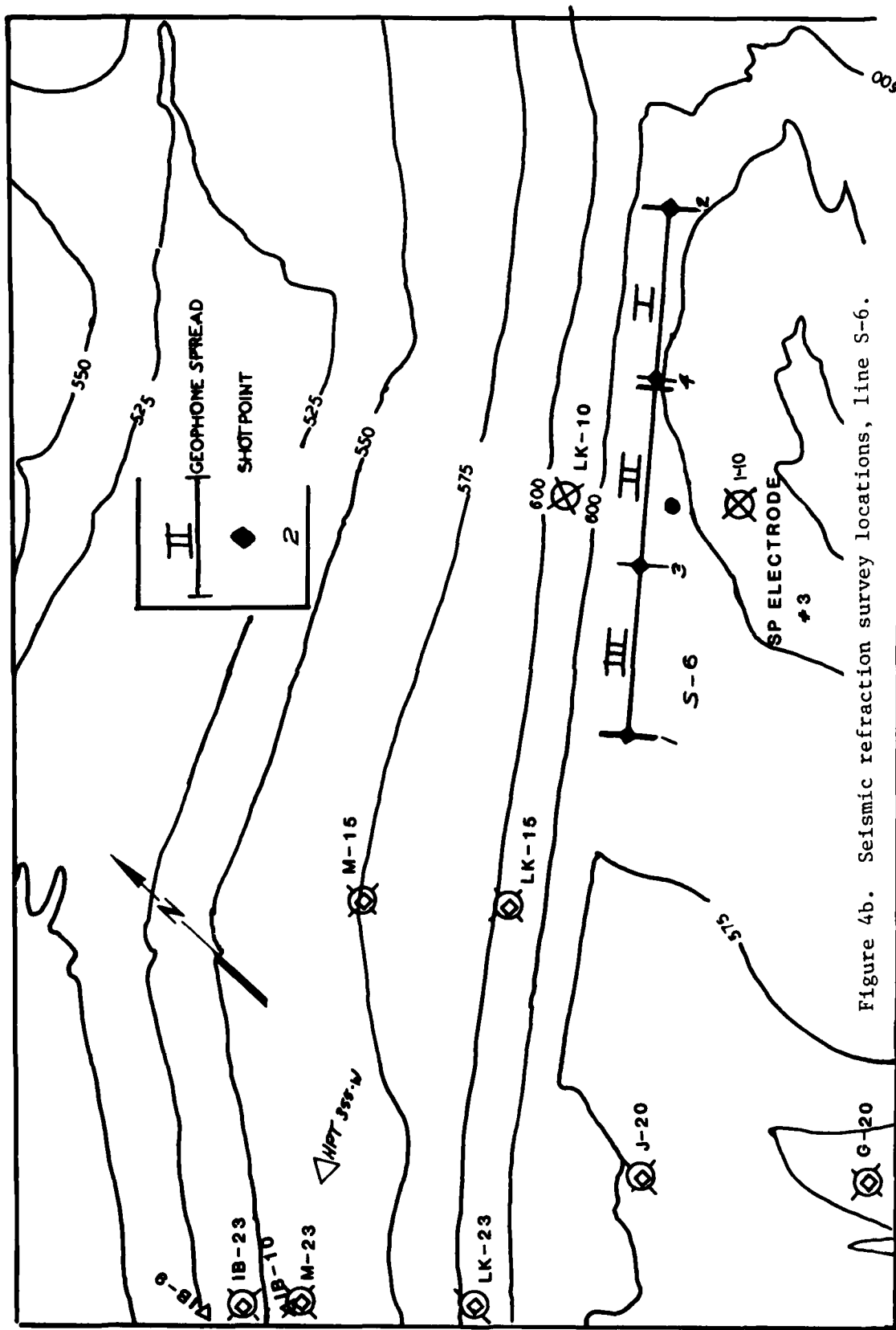
Figure 4b. Seismic refraction survey locations, line S-6.
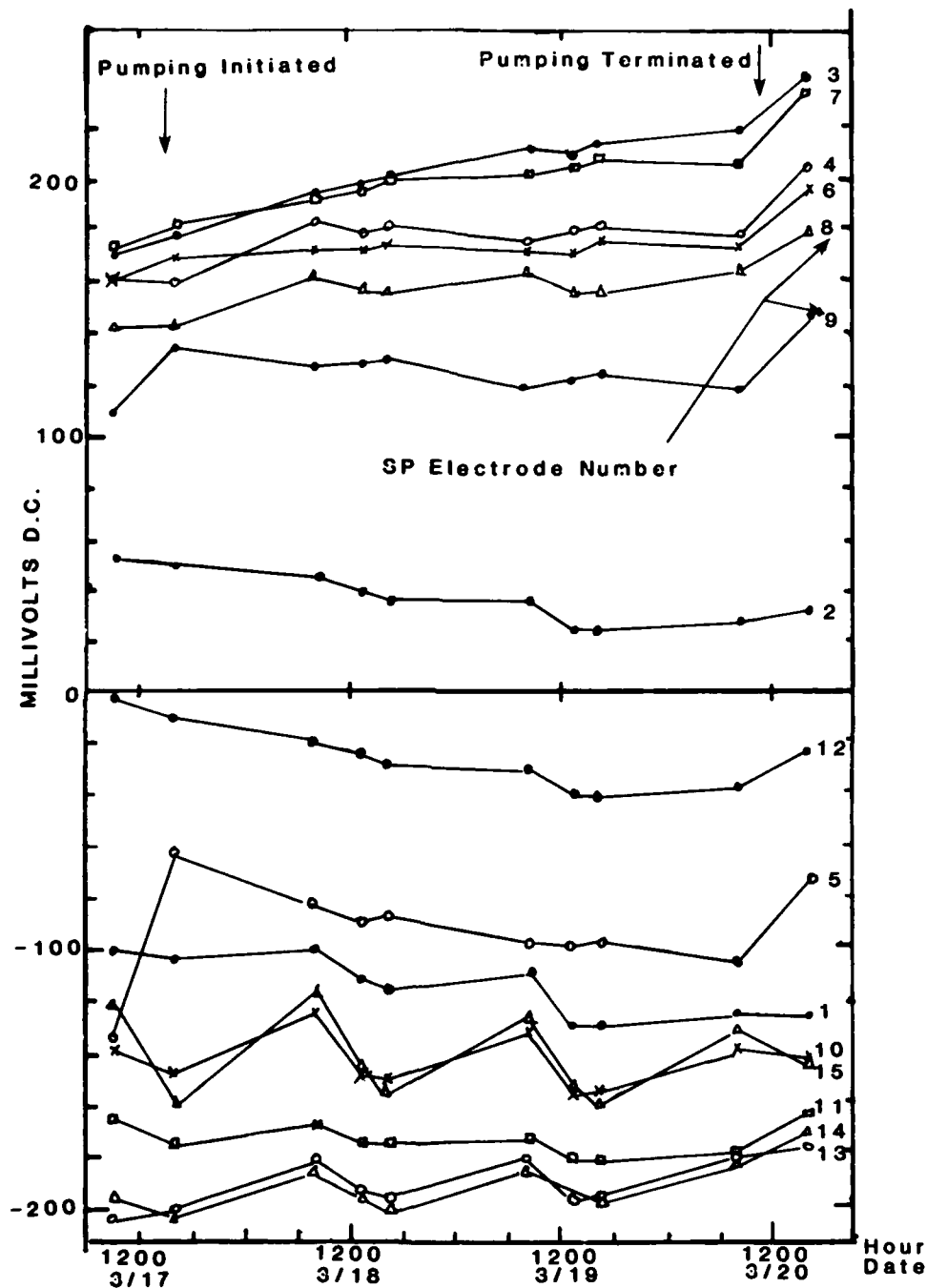
Figure 5.   Upstream SP Electrode Voltages as a
             Function of Time.
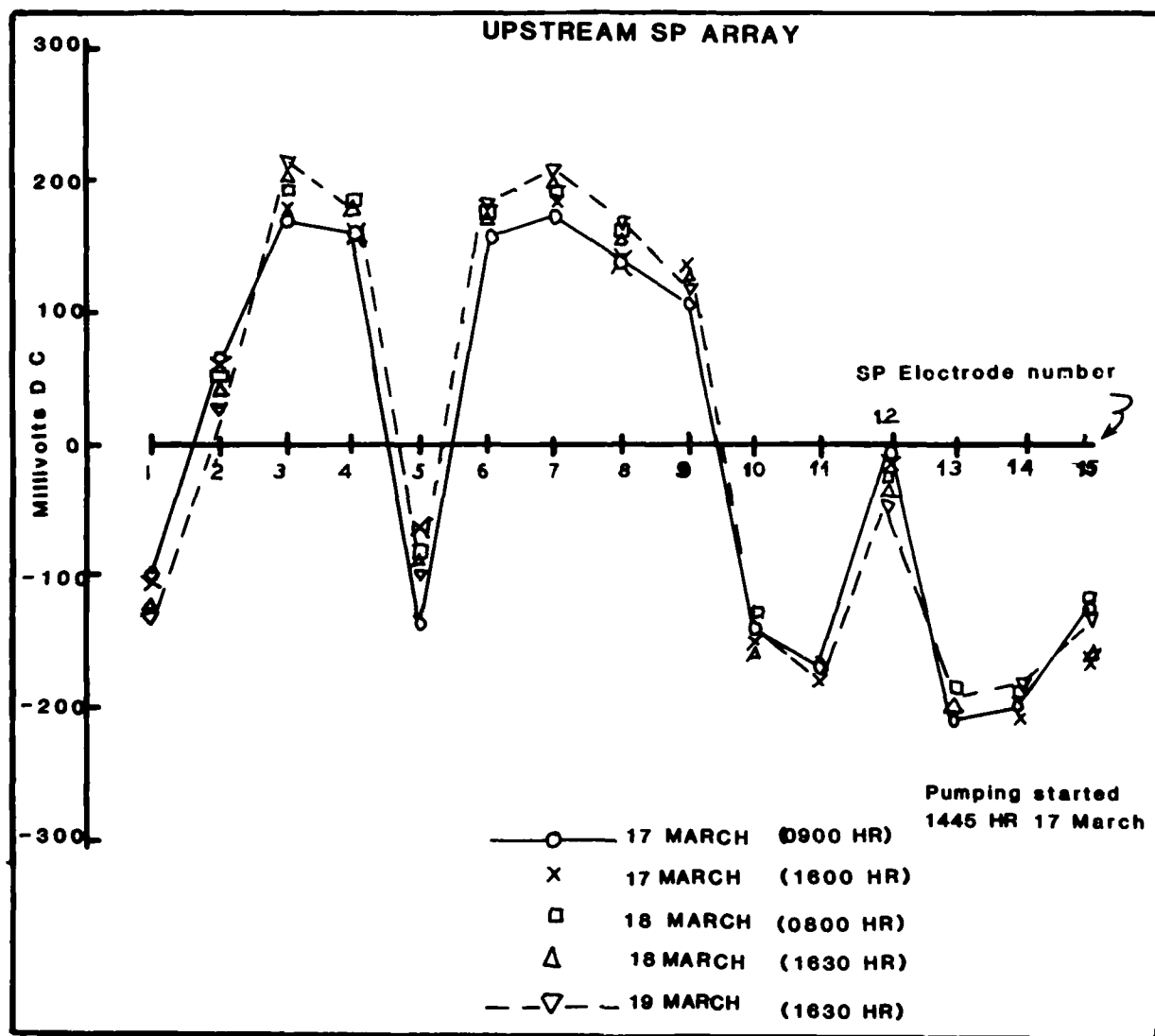
Figure 6. Static SP Profiles for Upstream Array.
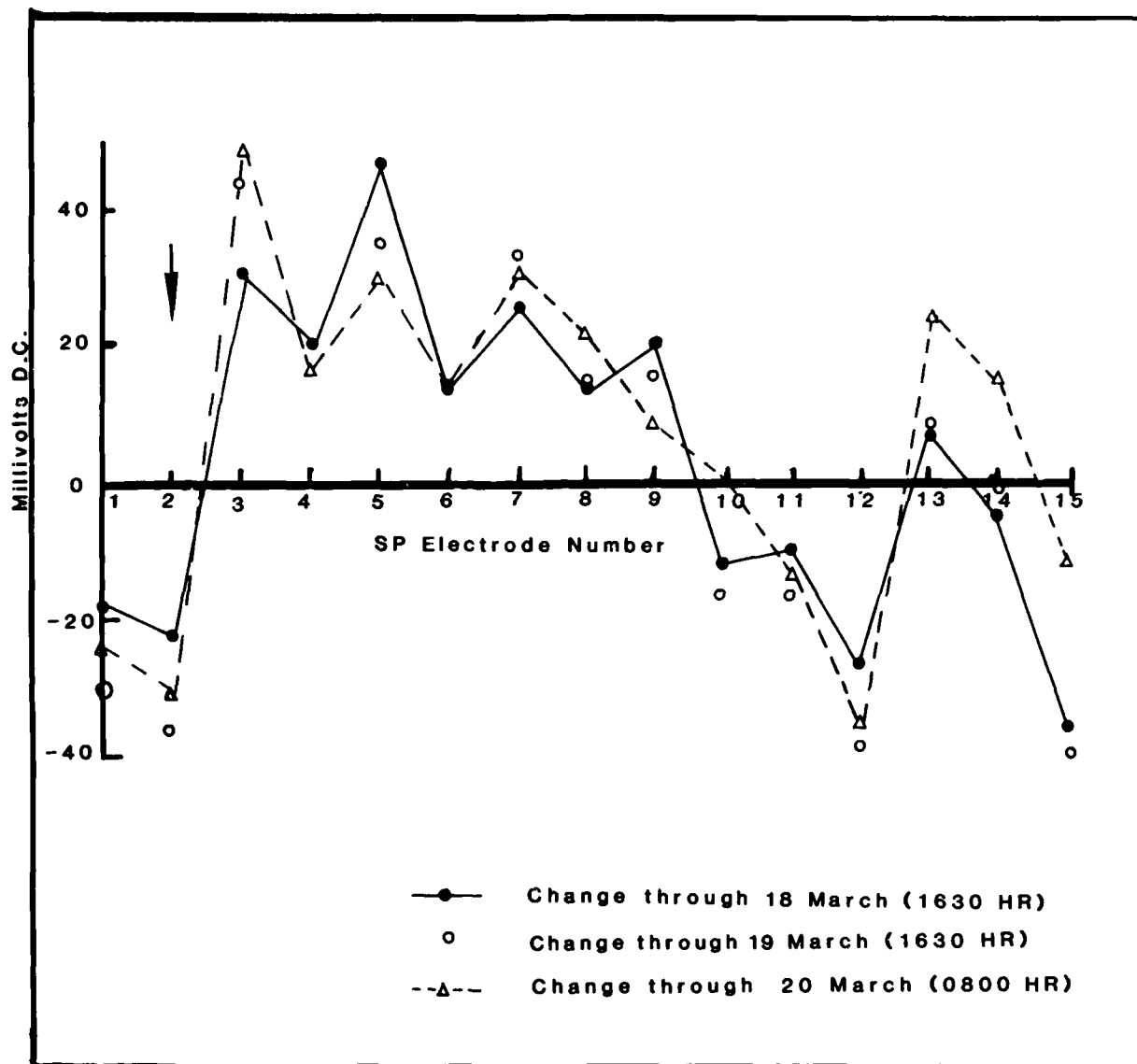
Figure 7.   Change in SP values at upstream array
            relative to reference values on March 17
            (0900 HR).
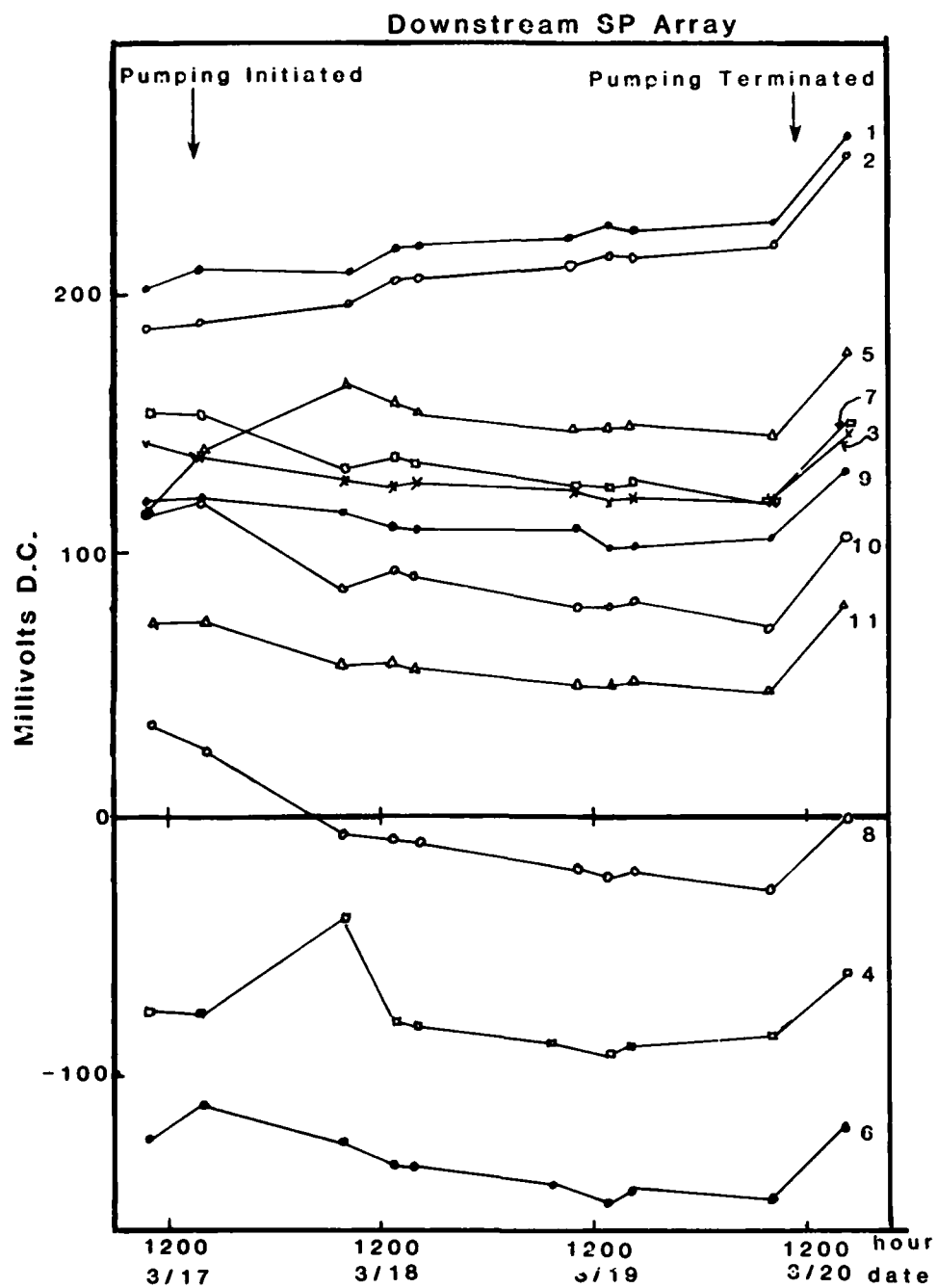
Figure 8.   Downstream SP Electrode Voltages as a
             Function of Time.
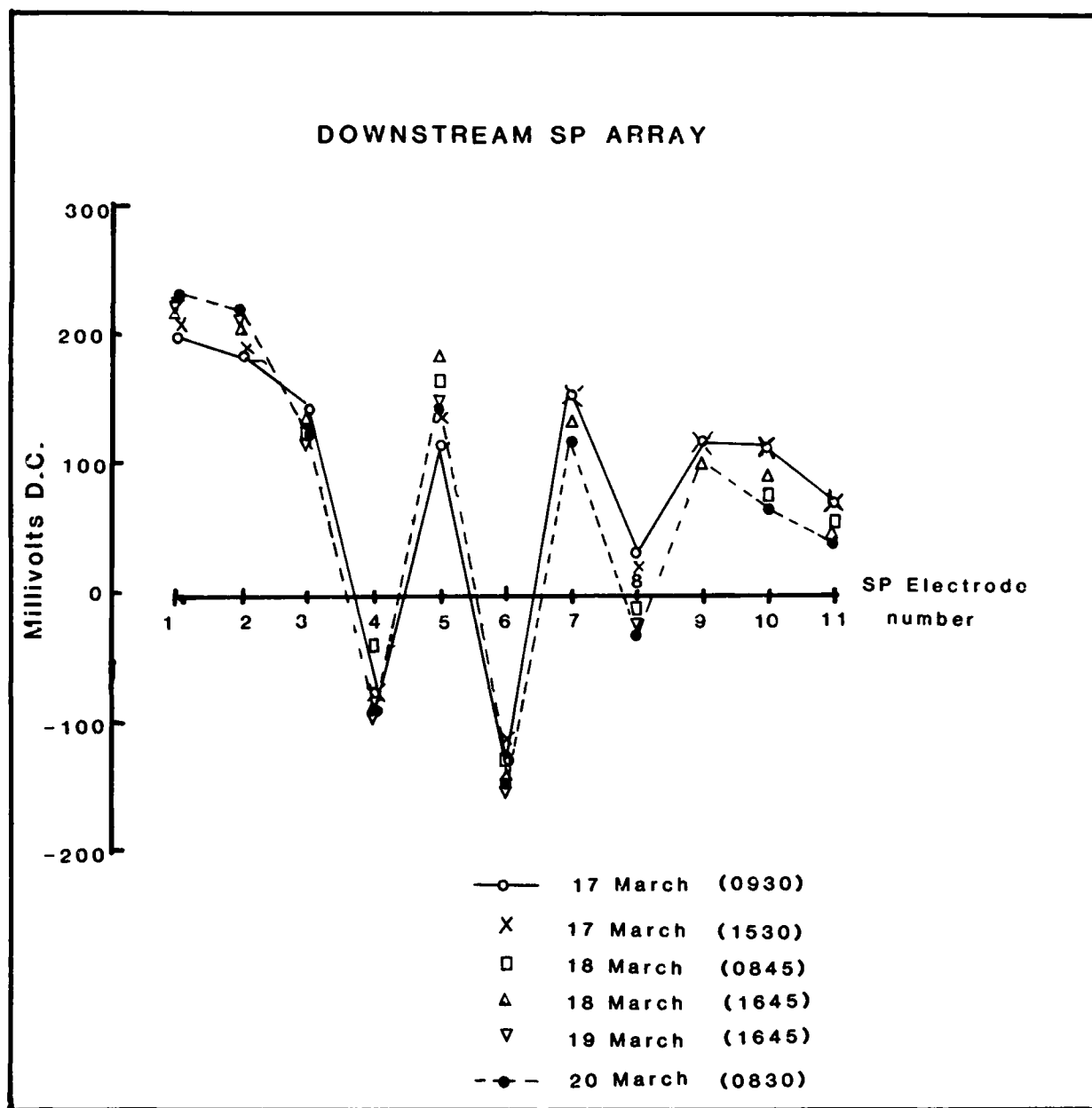
Figure 9.   Static SP Profiles for Downstream Array.
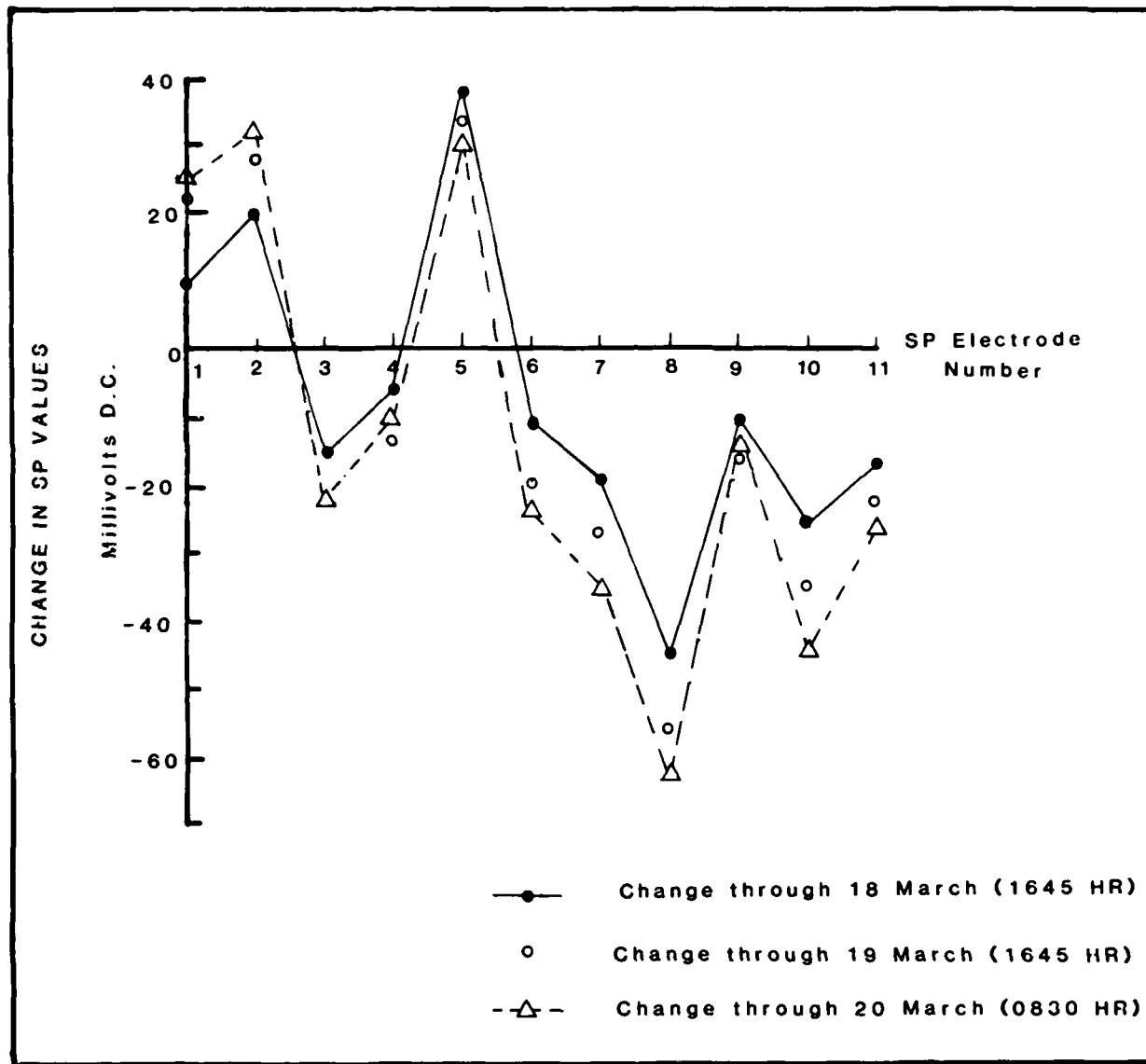
Figure 10. Change in SP Values at Downstream Array
Relative to Reference Values on March 17
(0900).
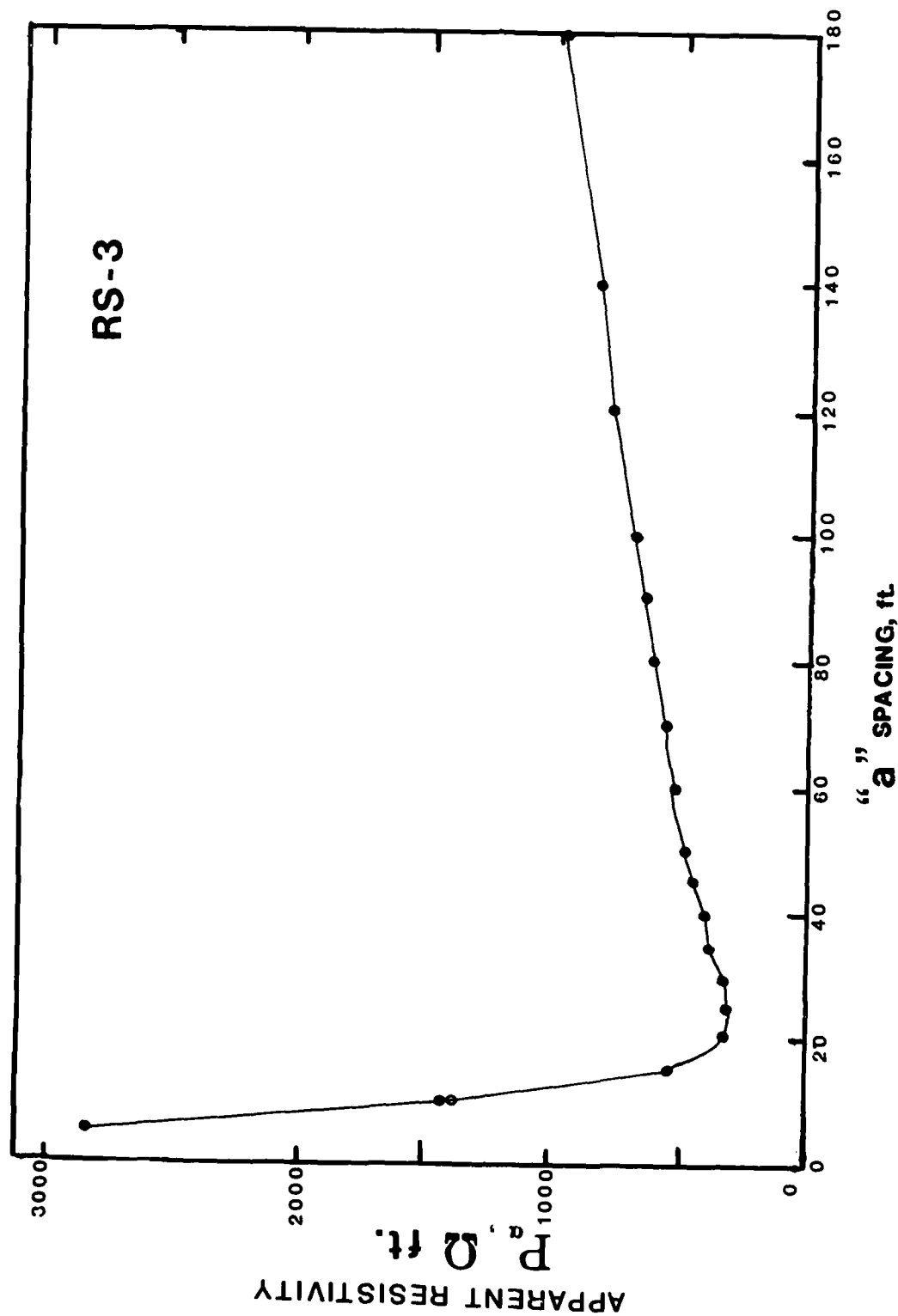
Figure 11a. Resistivity Sounding (Wenner Array) Curve (RS-3). Centered on Upstream SP Electrode 7.

POSSIBLE
INTERPRETATION

INTERFACE Depth, ft.	LAYER Resistivity, Ω-ft.
0	3000
5	1000
11	1000
	180
35	
	1000
70	
	3000

5 ft. Data

10 ft. Data

20 ft. Data

ΣP_a, Ω-ft.

7000

6000

5000

4000

3000

2000

1000

0

11 ft.

35 ft.

70 ft.

5 ft.

0   20   40   60   80   100   120   140

"a", ft.
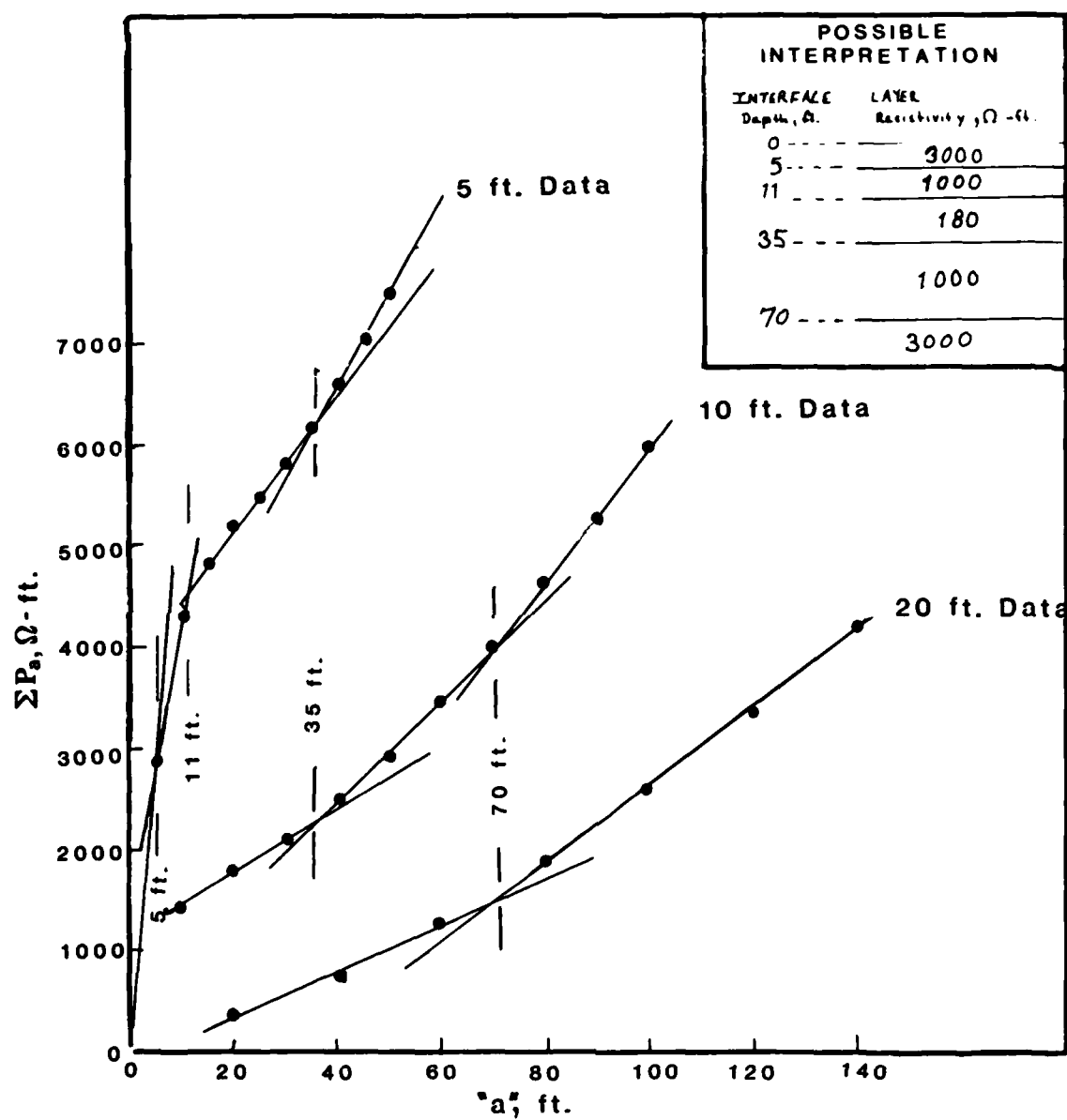
Figure 11b. Cumulative Resistivity Plot for RS-3.

ELECTRODE SPACING, a, Ft (10's)

APPARENT RESISTIVITY, Ohm-ft (1000's)
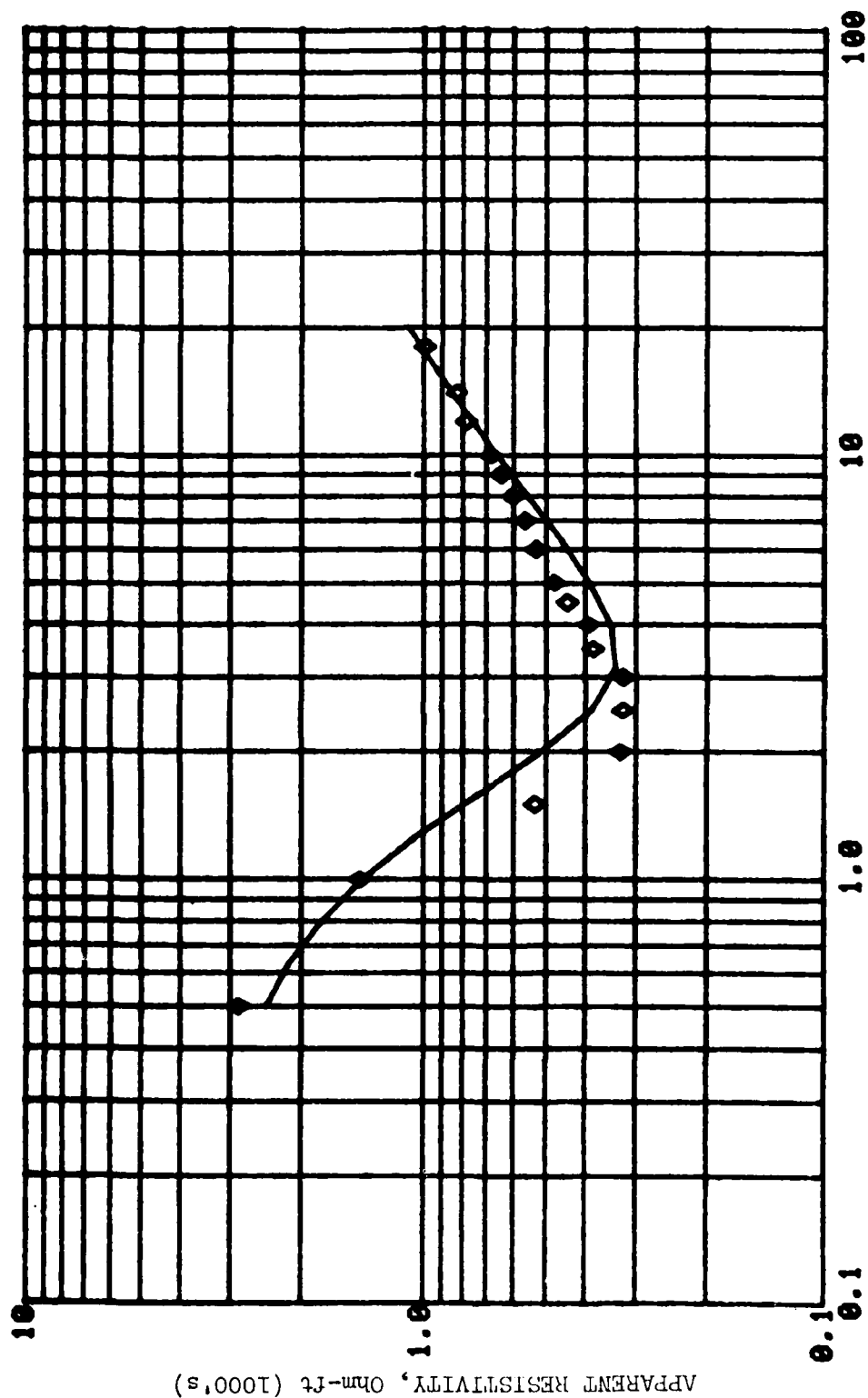
Figure 11c. Comparison of resistivity models from Figure 11b
(solid line) with field data (symbols) for
Wenner Sounding RS-3.

Figure 12. Horizontal Resistivity Profile Along Upstream
SP Array (Wenner Array, a = 50 ft), RP-4.
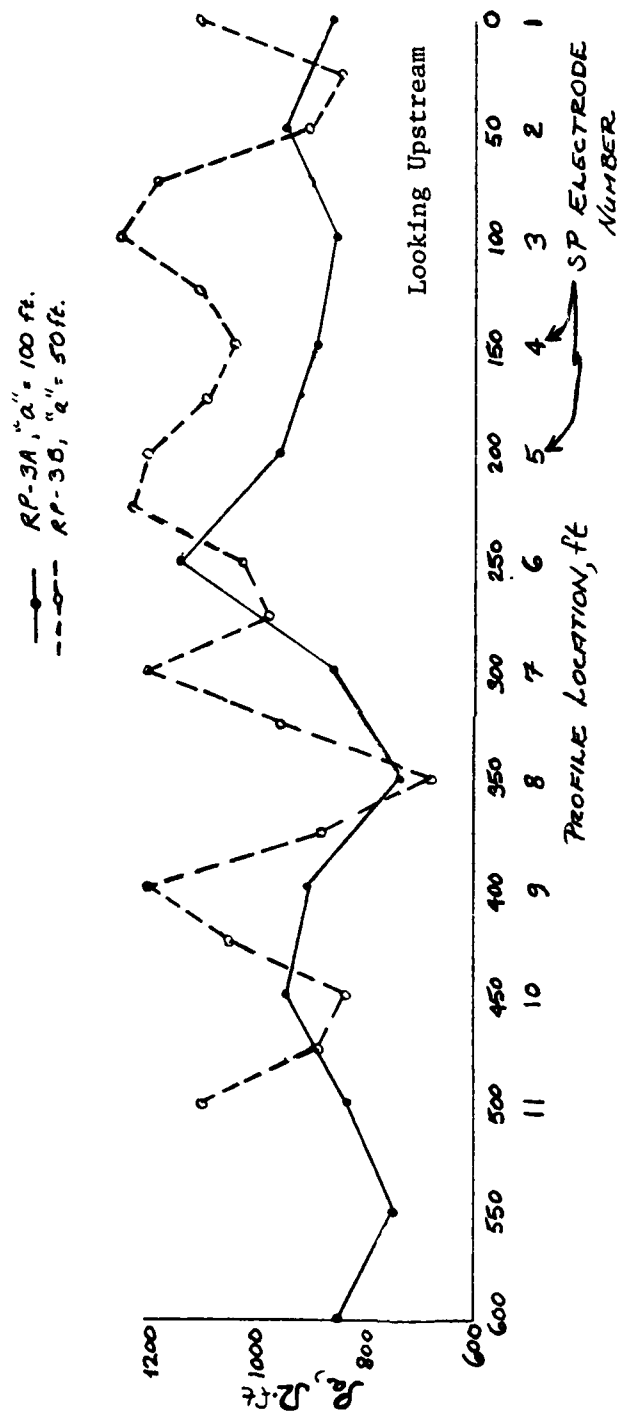
Figure 13. Horizontal Resistivity Profiles Along Downstream
SP Array for a = 50 ft (RP-313) and a = 100 ft (RP-3A).
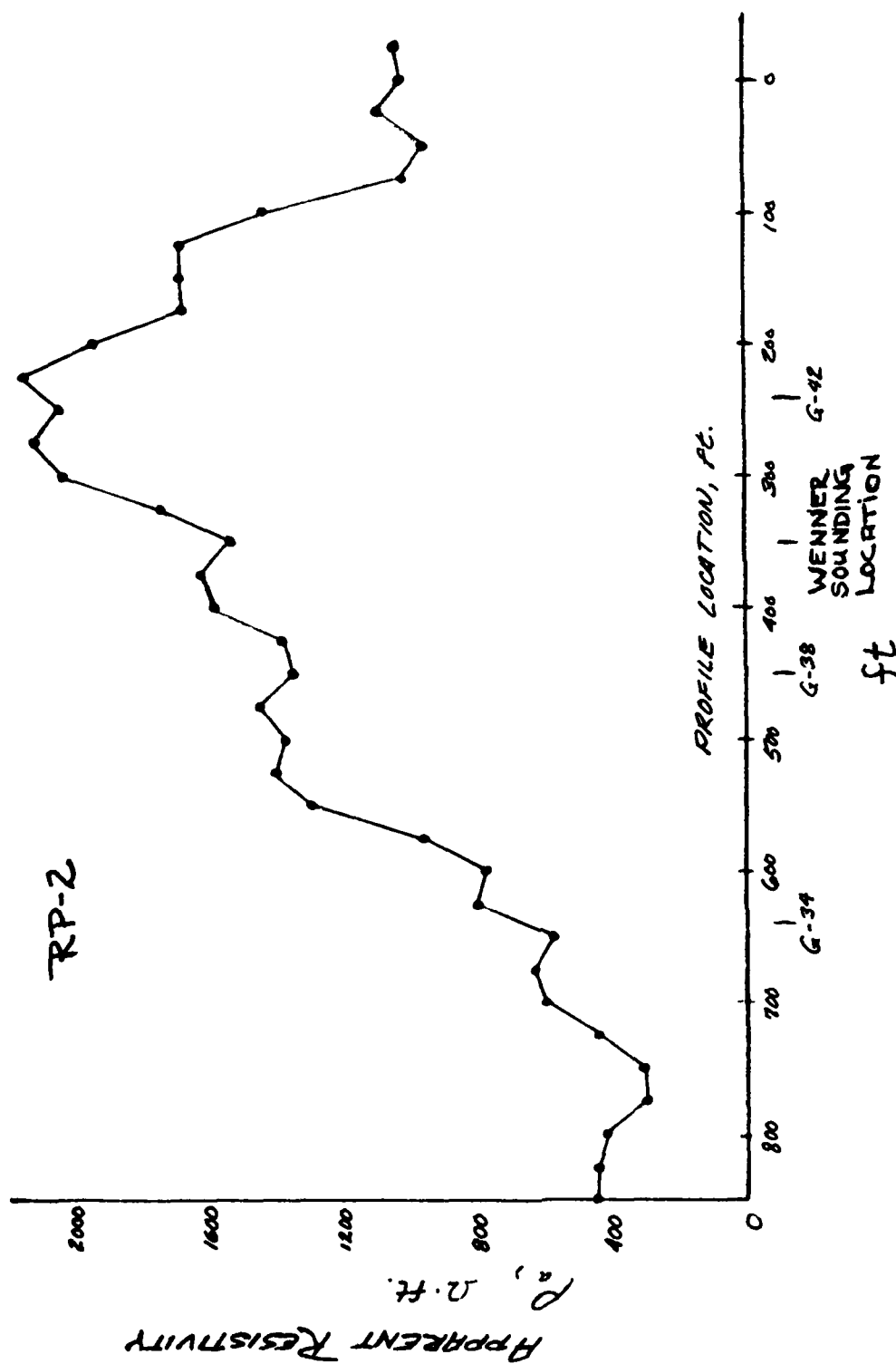
Figure 14. Horizontal Resistivity Profile Along Downstream Toe
Piezometer Line (a = 50 ft). Boring Locations Indicated.

Figure 15a. Vertical Resistivity Sounding, RS-1, Centered
Between G-42 and G-38 (100 ft from G-38)
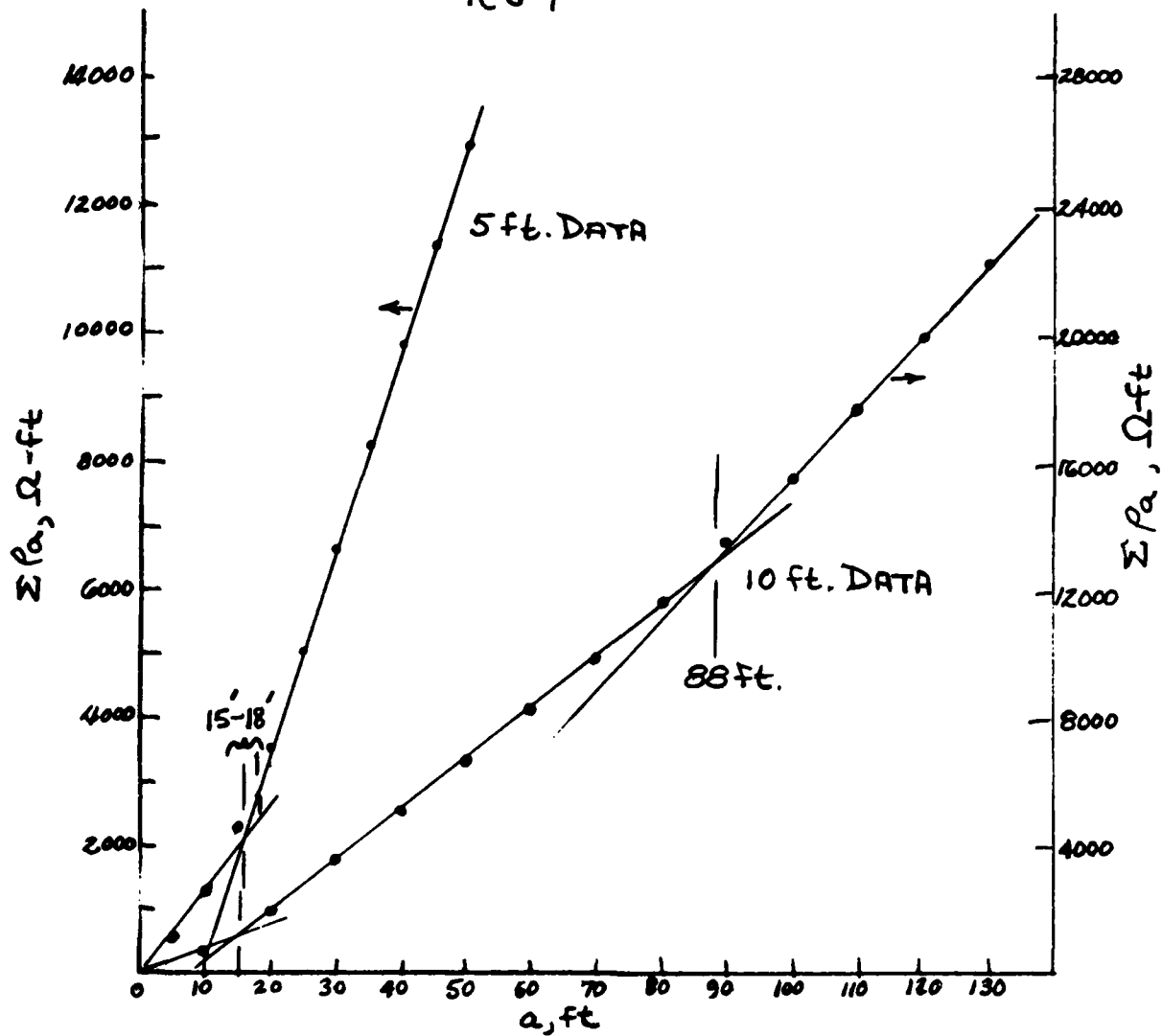
Figure 15b.   Cumulative Resistivity Plot for RS-1

TOE OF
DAM ——→ TO LEFT ABUTMENT

Contour Interval - 100 ohm-ft

G-47
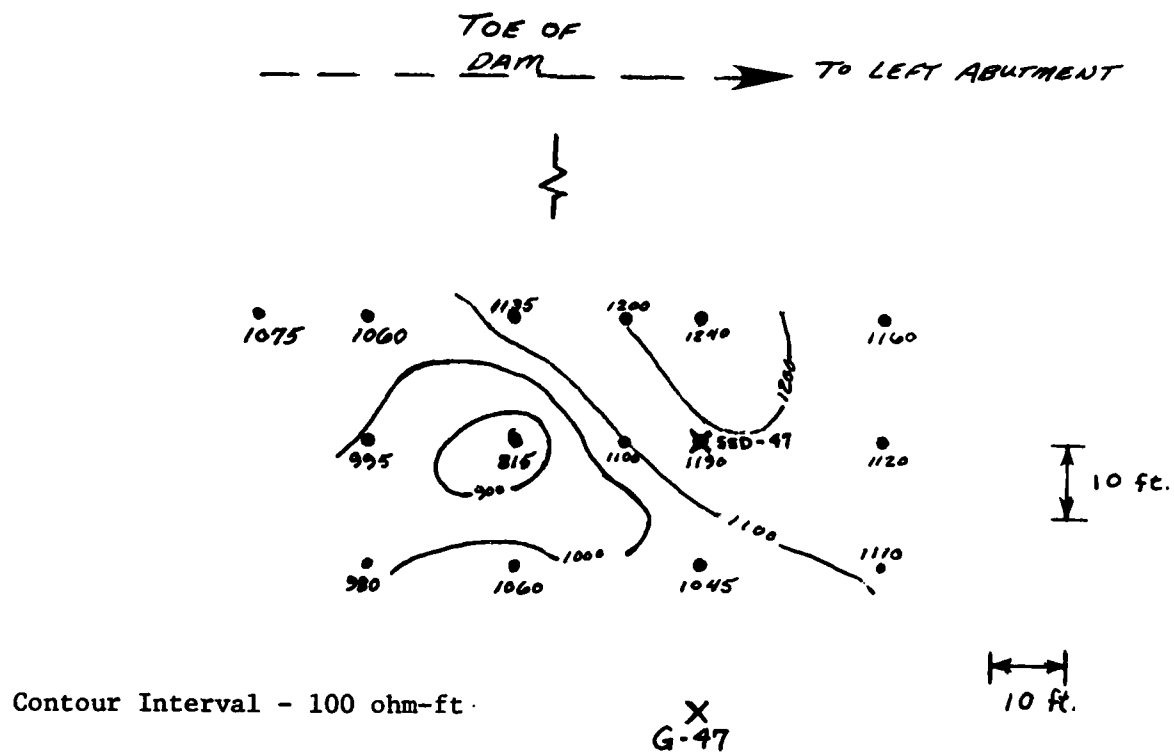
(Note: Resistivity for a = 80 ft centered on 550-47 = 1670 ohm-ft)

Figure 16. Resistivity Values on Grid Around Boring 550-47,

Wenner Array - a + 50 ft, WG-1
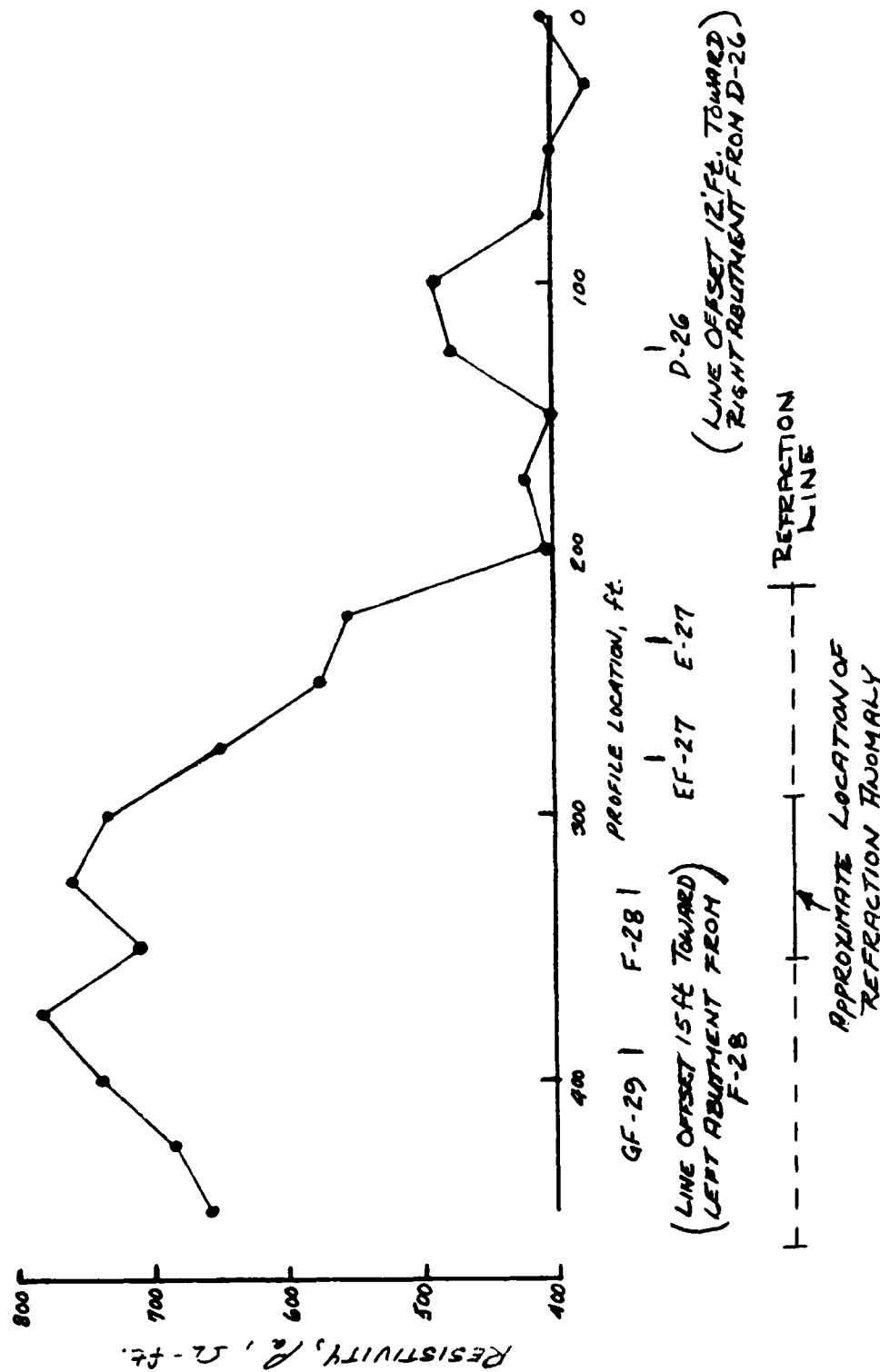
Figure 17. Horizontal resistivity profile along base of left abutment
ridge, a = 50 ft, line RP-1
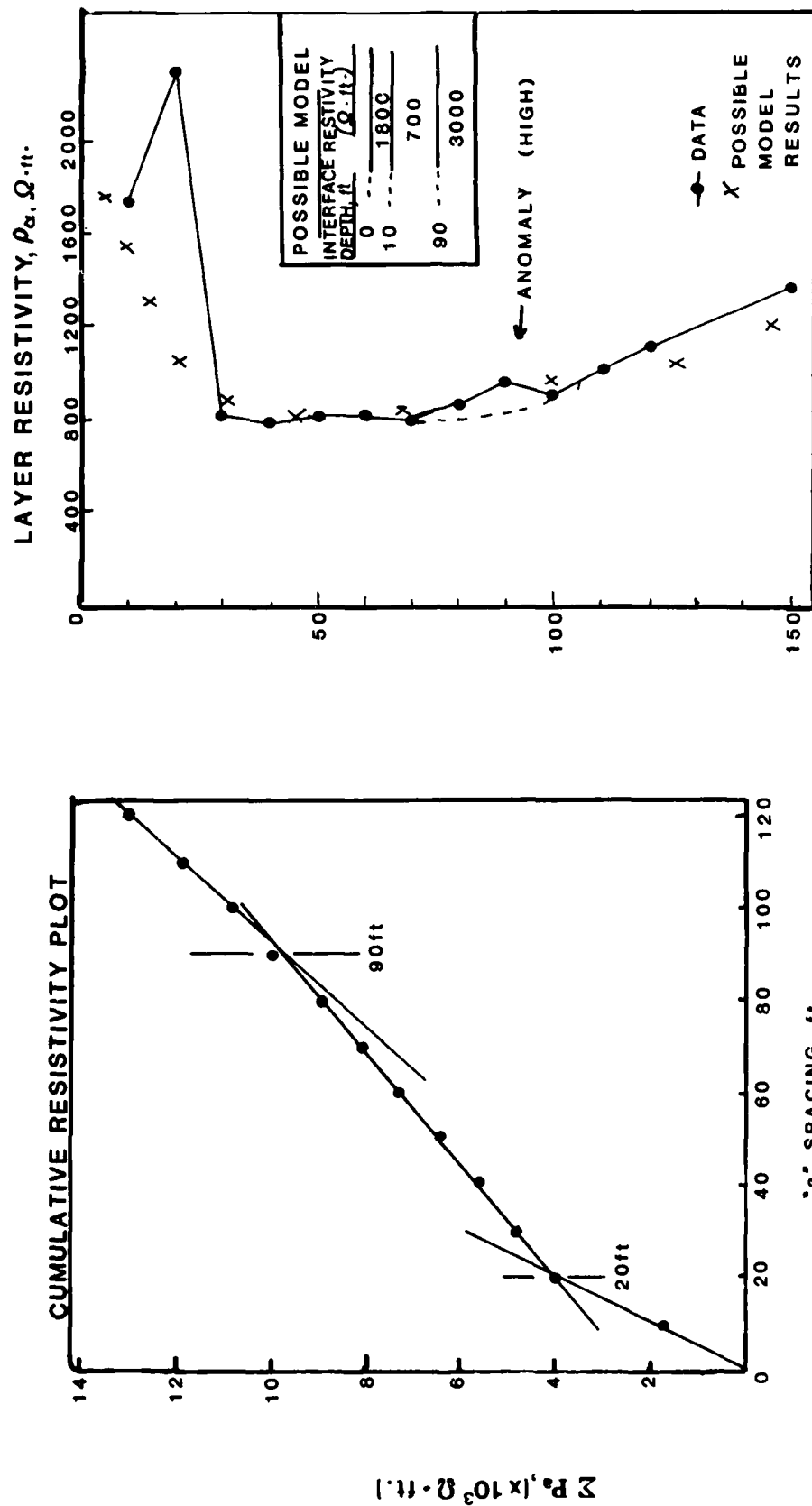
Figure 18. Vertical Resistivity Sounding centered at Boring
G-23 on First Left Abutment Ridge. RS-2.
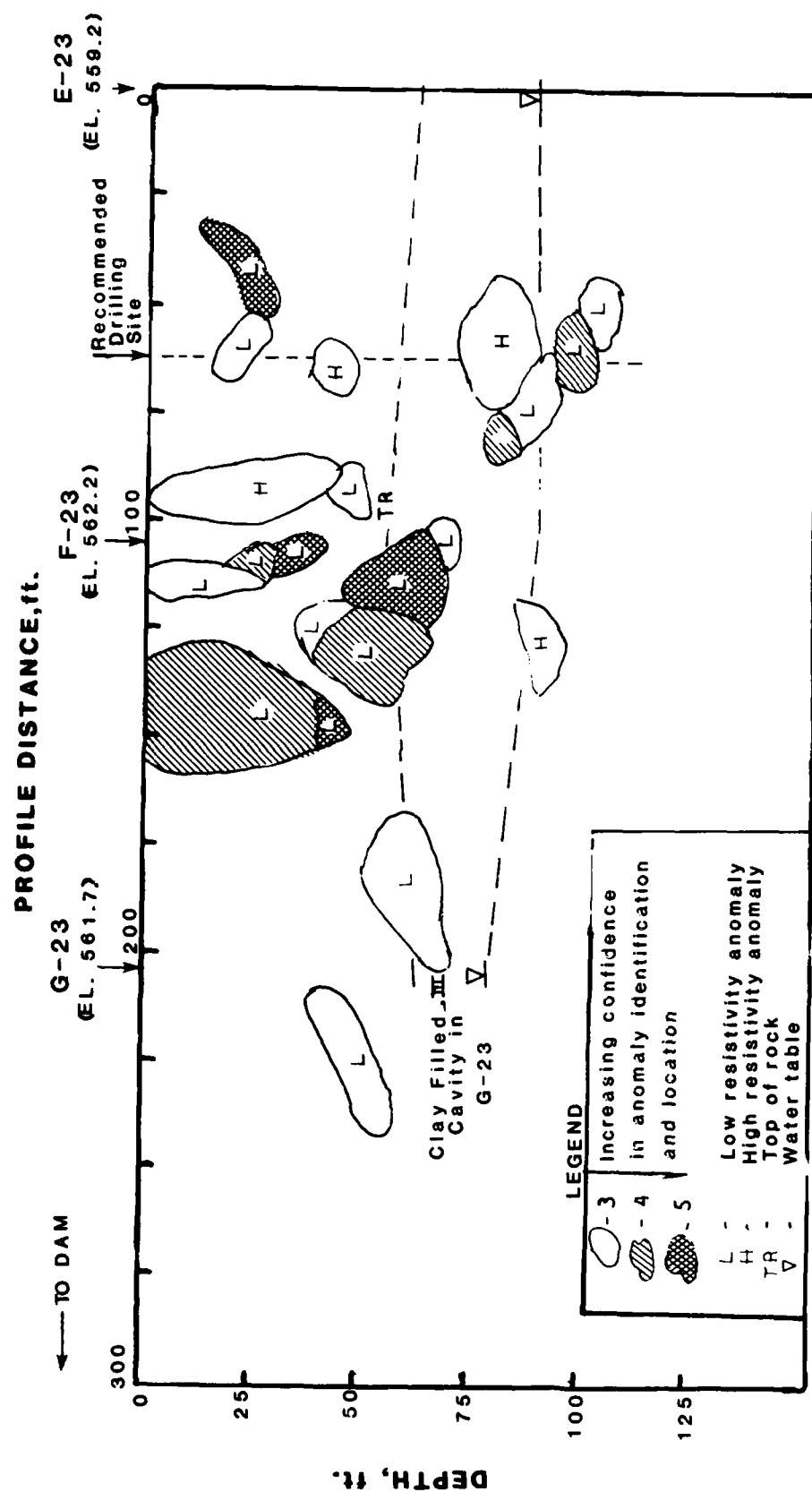
Figure 19. Pole-dipole survey results, B-1, top of first left abutment ridge, ⊥ to axis of dam.
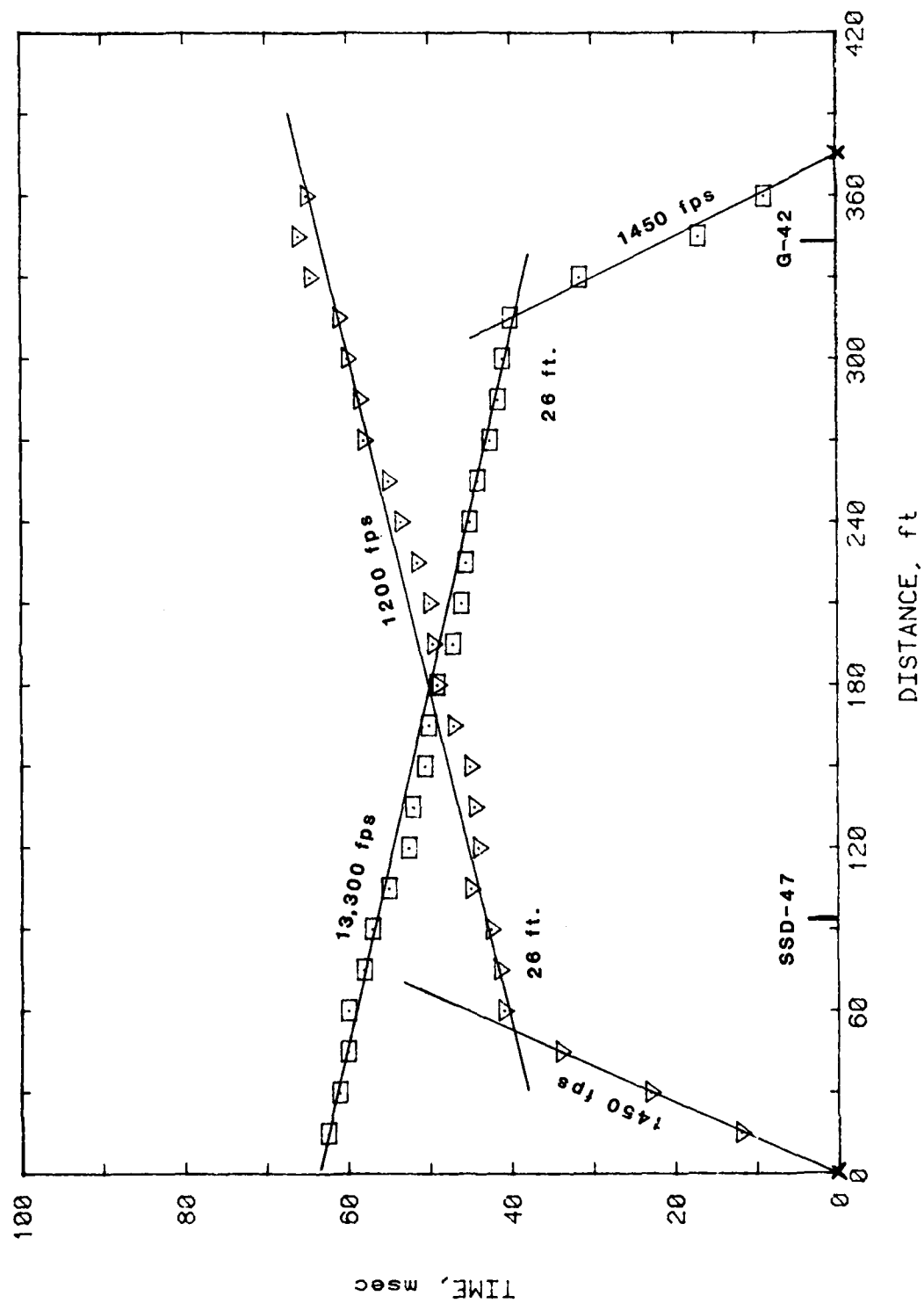
Figure 20. Time versus distance plot for refraction line S-1
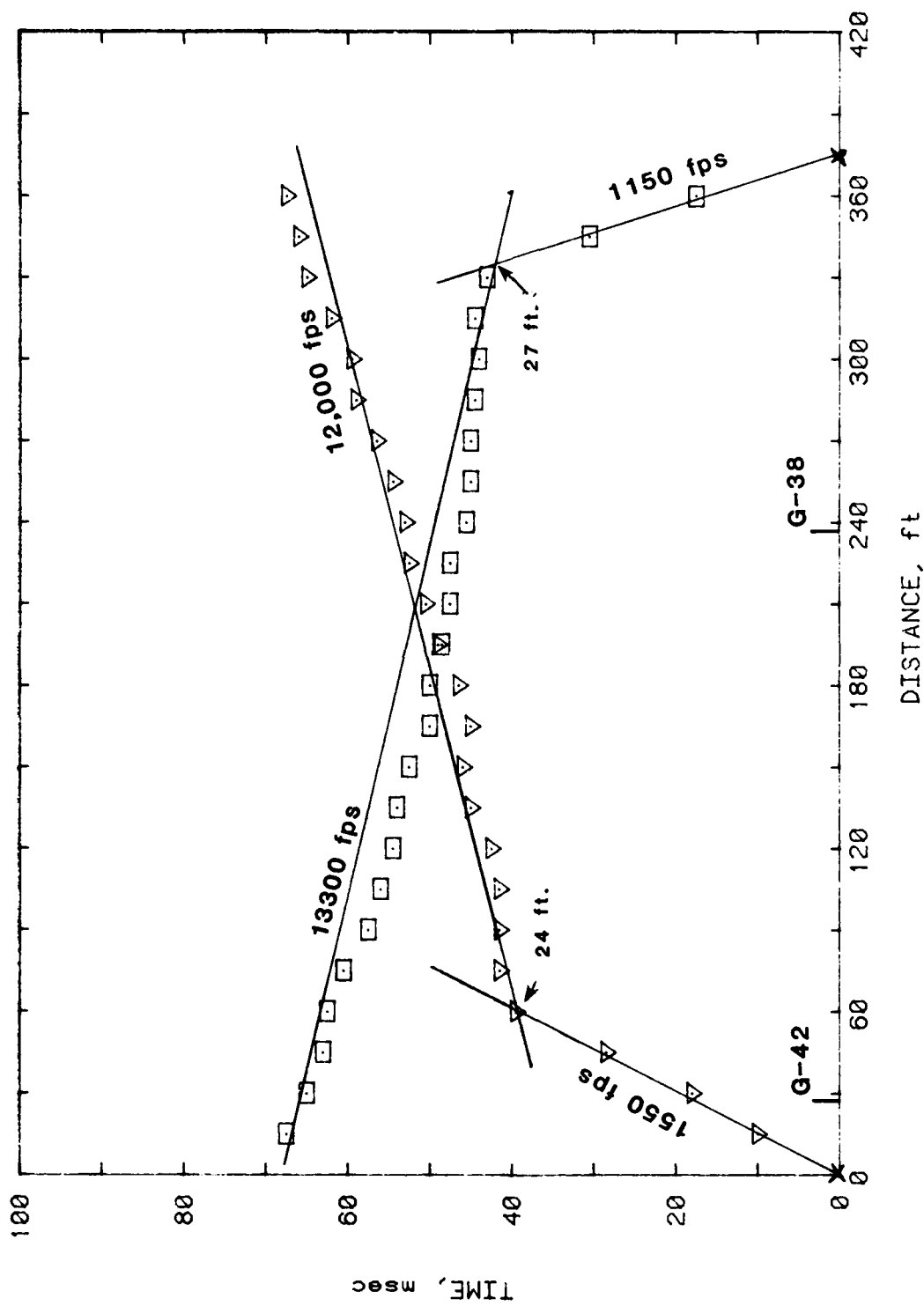
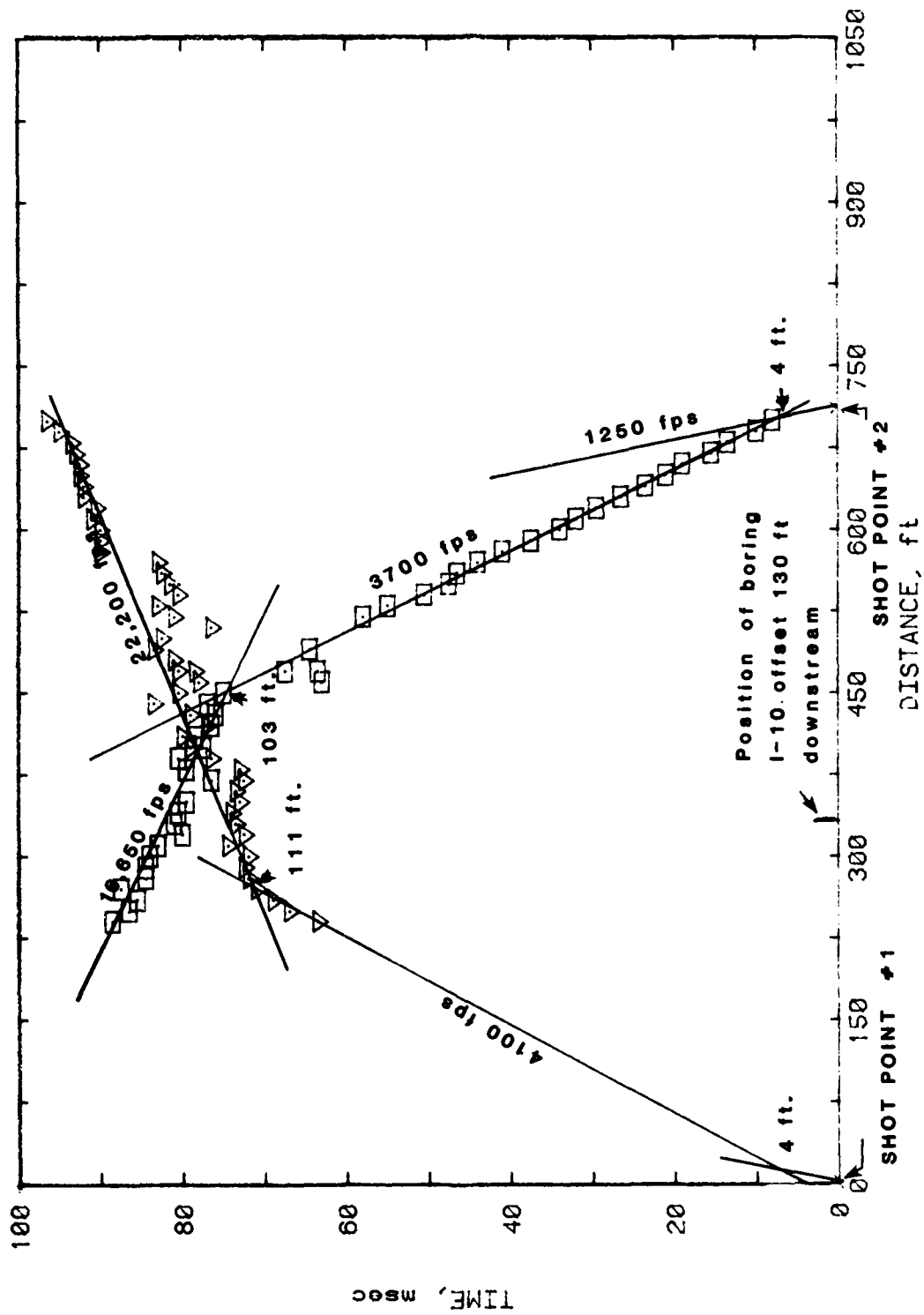Figure 21. Time versus distance plot for refraction line S-2
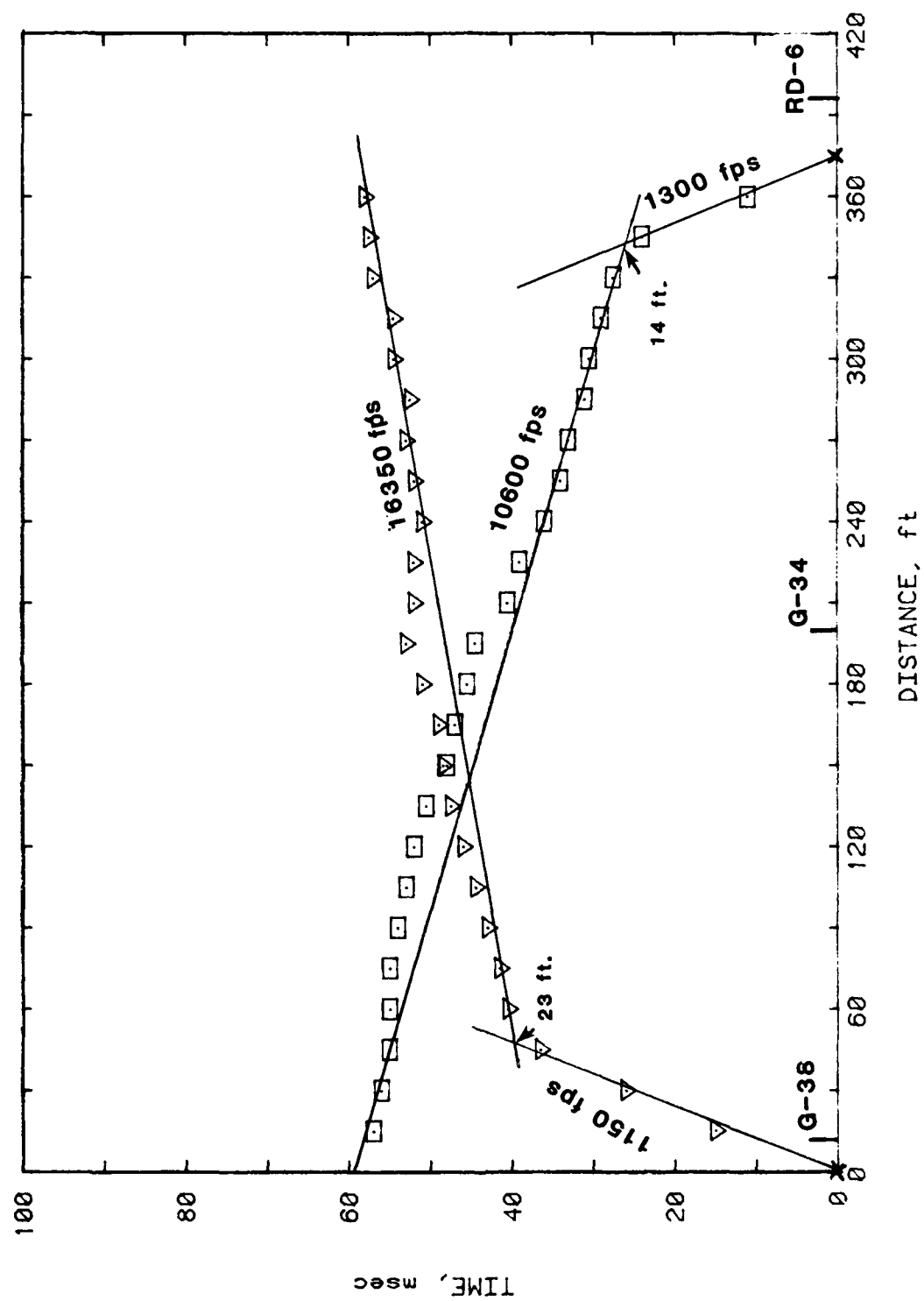
Figure 22. Time versus distance plot for refraction line S-3
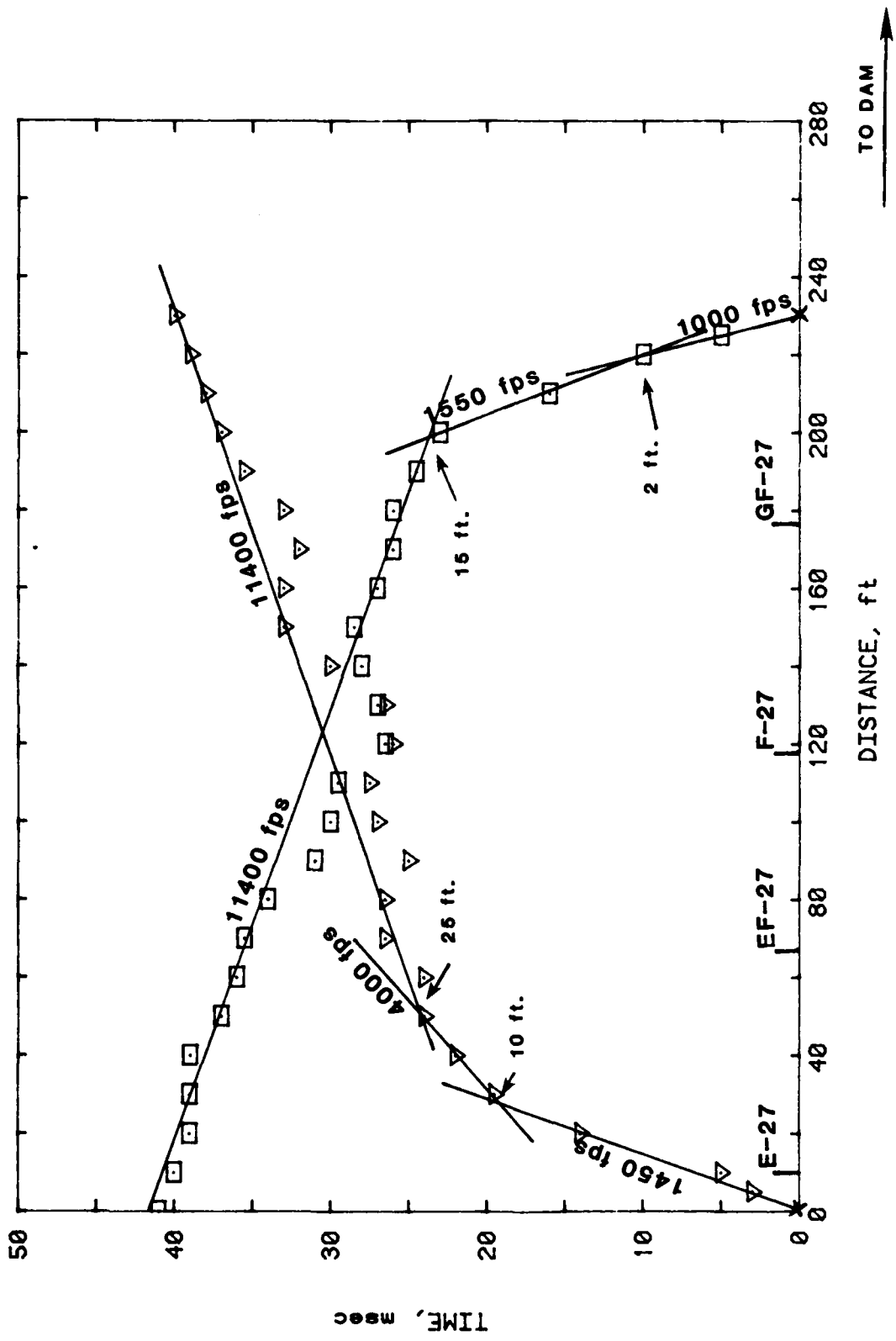
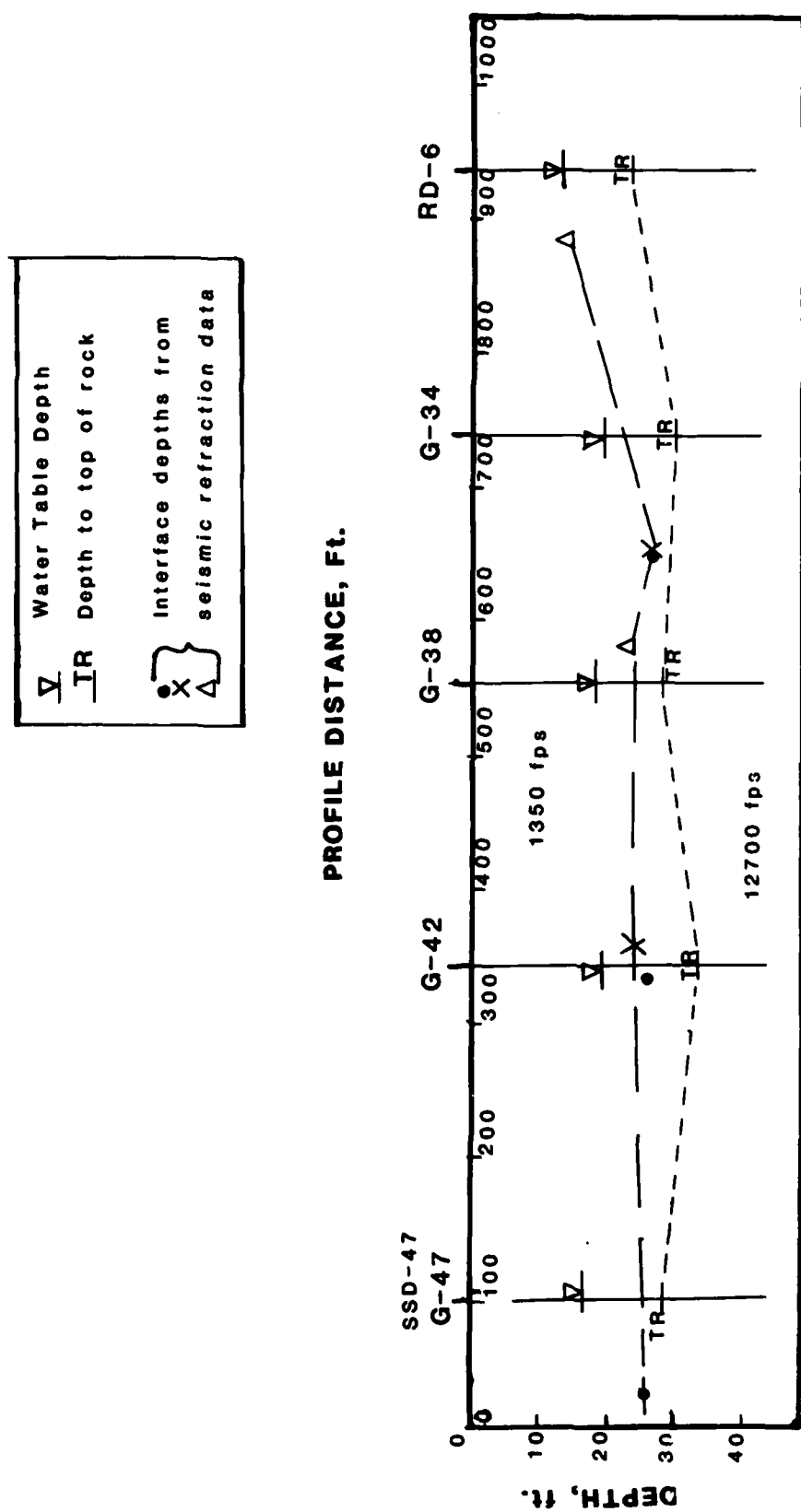Figure 23. Time versus distance plot for refraction line S-4
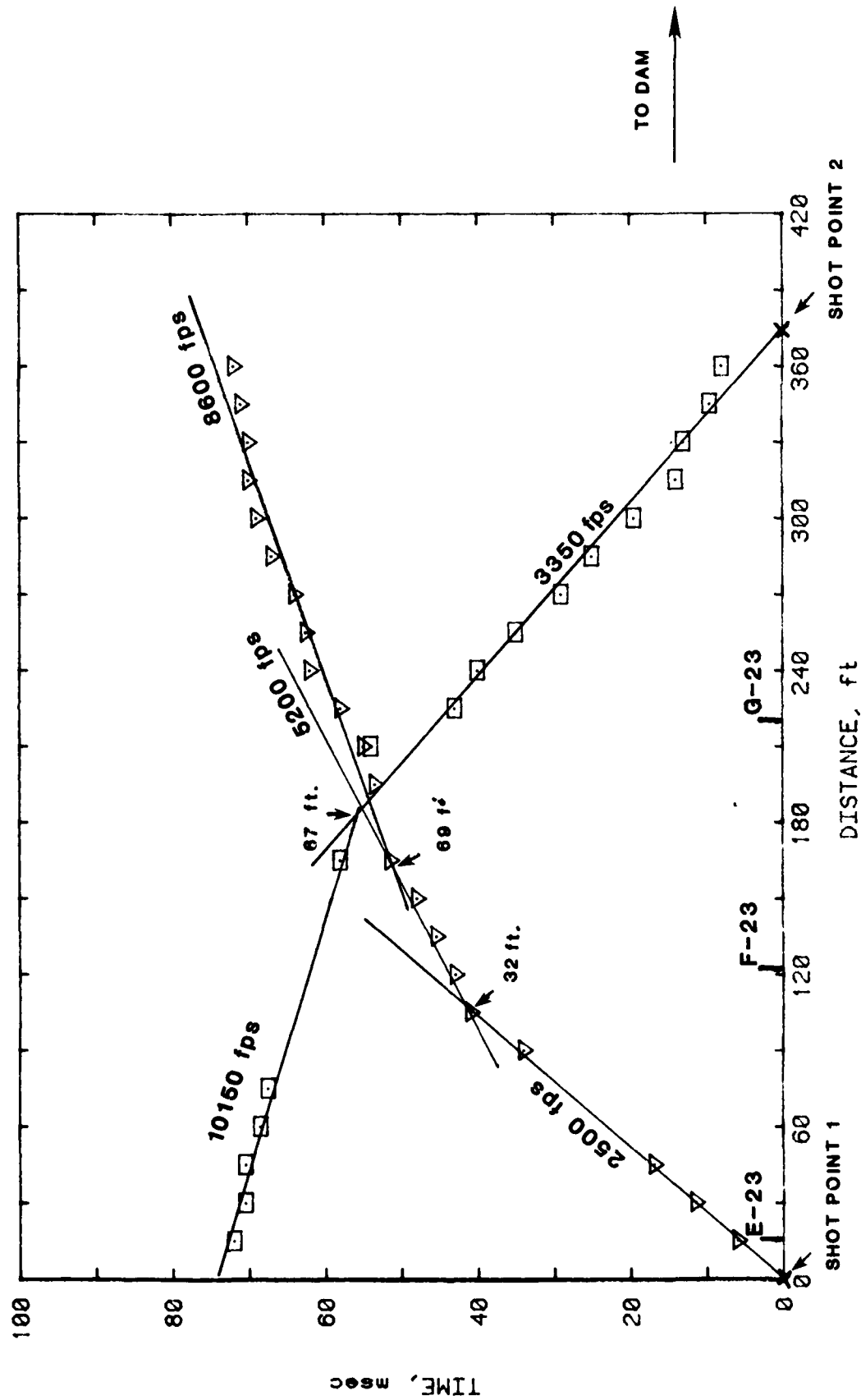
Figure 24. Time versus distance plots for refraction line S-5
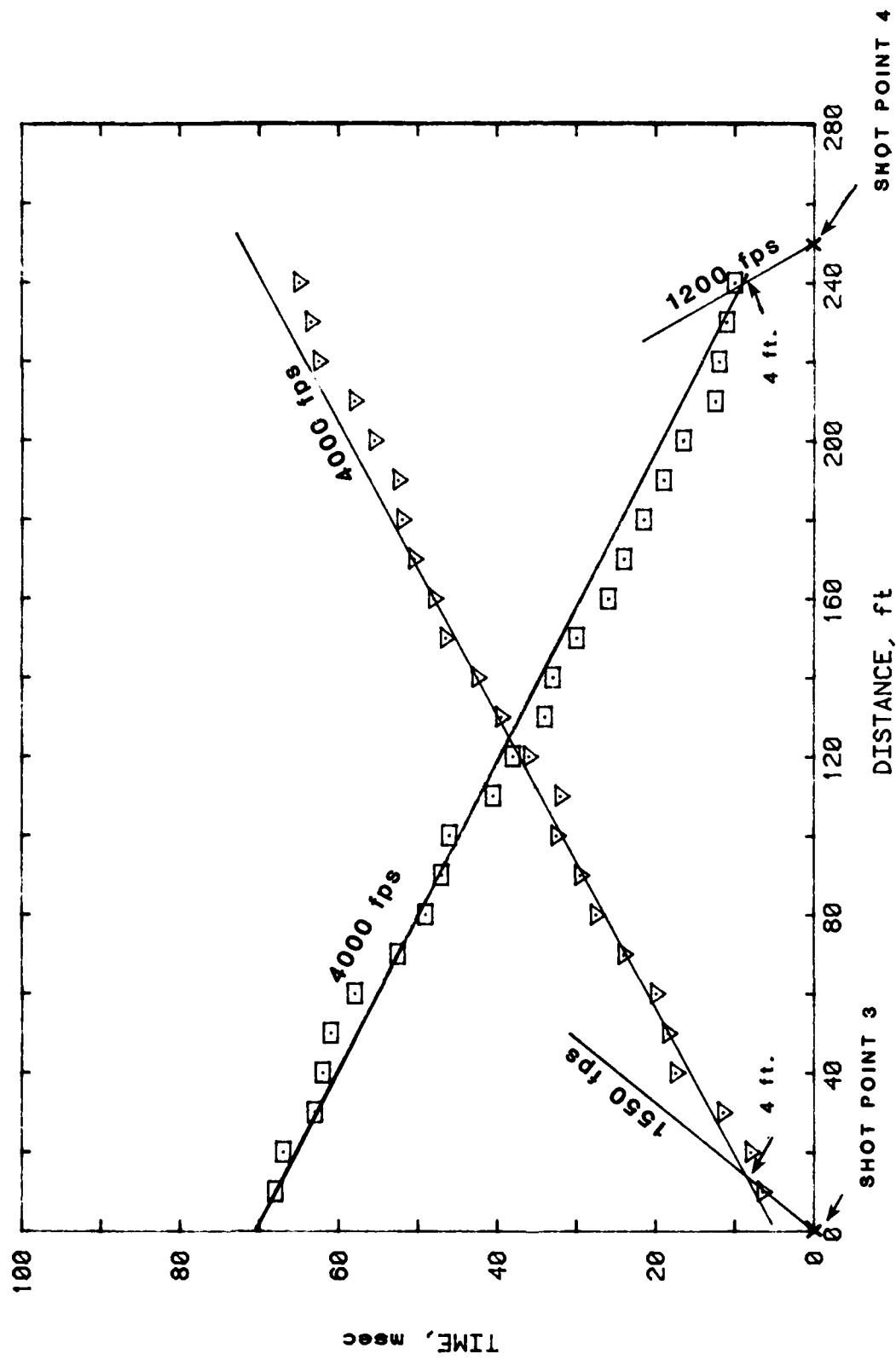
Figure 25. Time versus distance plot for refraction line S-6B

Figure 26. Time versus distance plot for refraction line S-6A

Figure 27. Cross-Section Data Along Downstream Toe of dam, Seismic Refraction Lines S-1, S-2, and S-3.
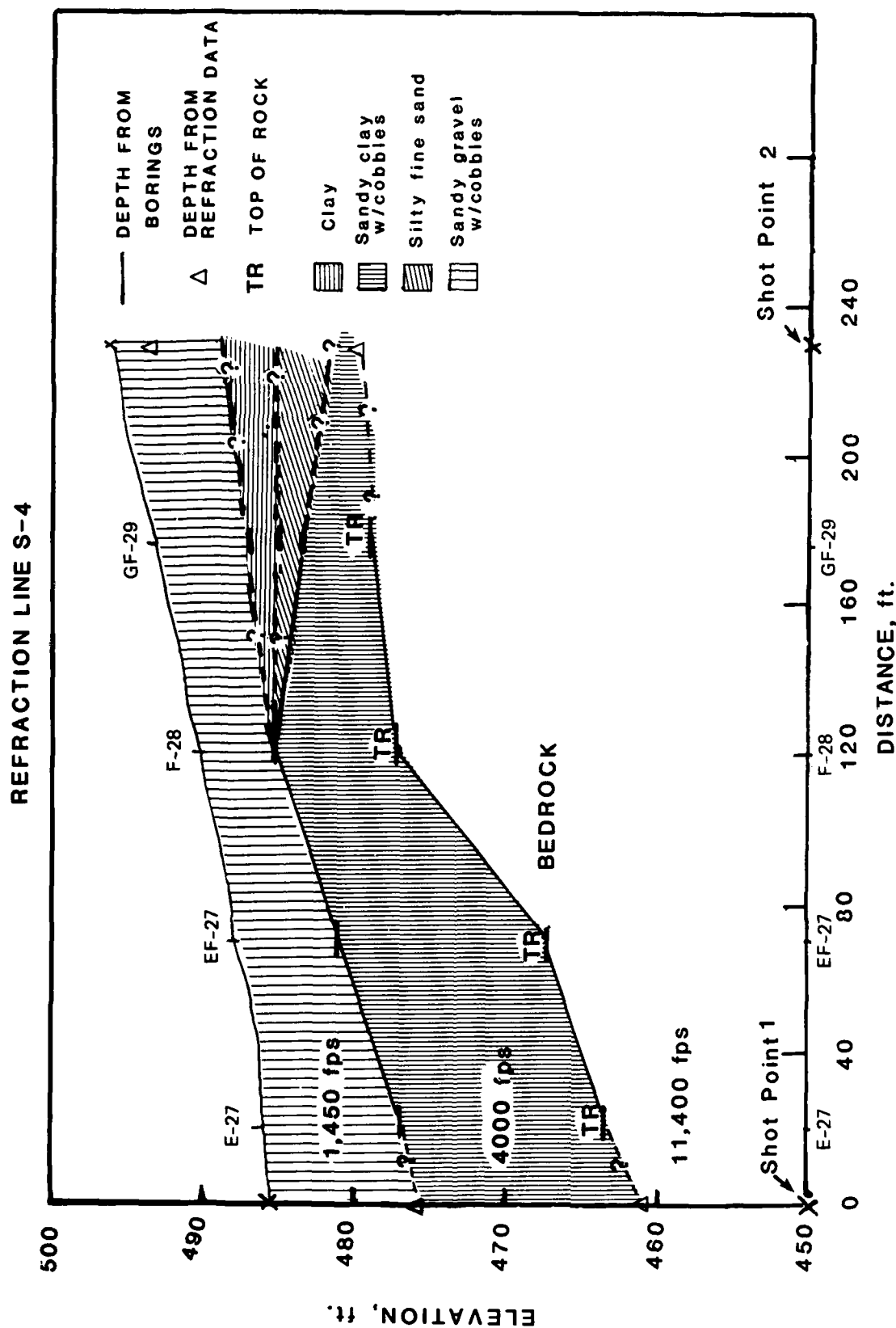
Figure 28. Cross section along base of left abutment ridge showing refraction interpretation and borehole data.
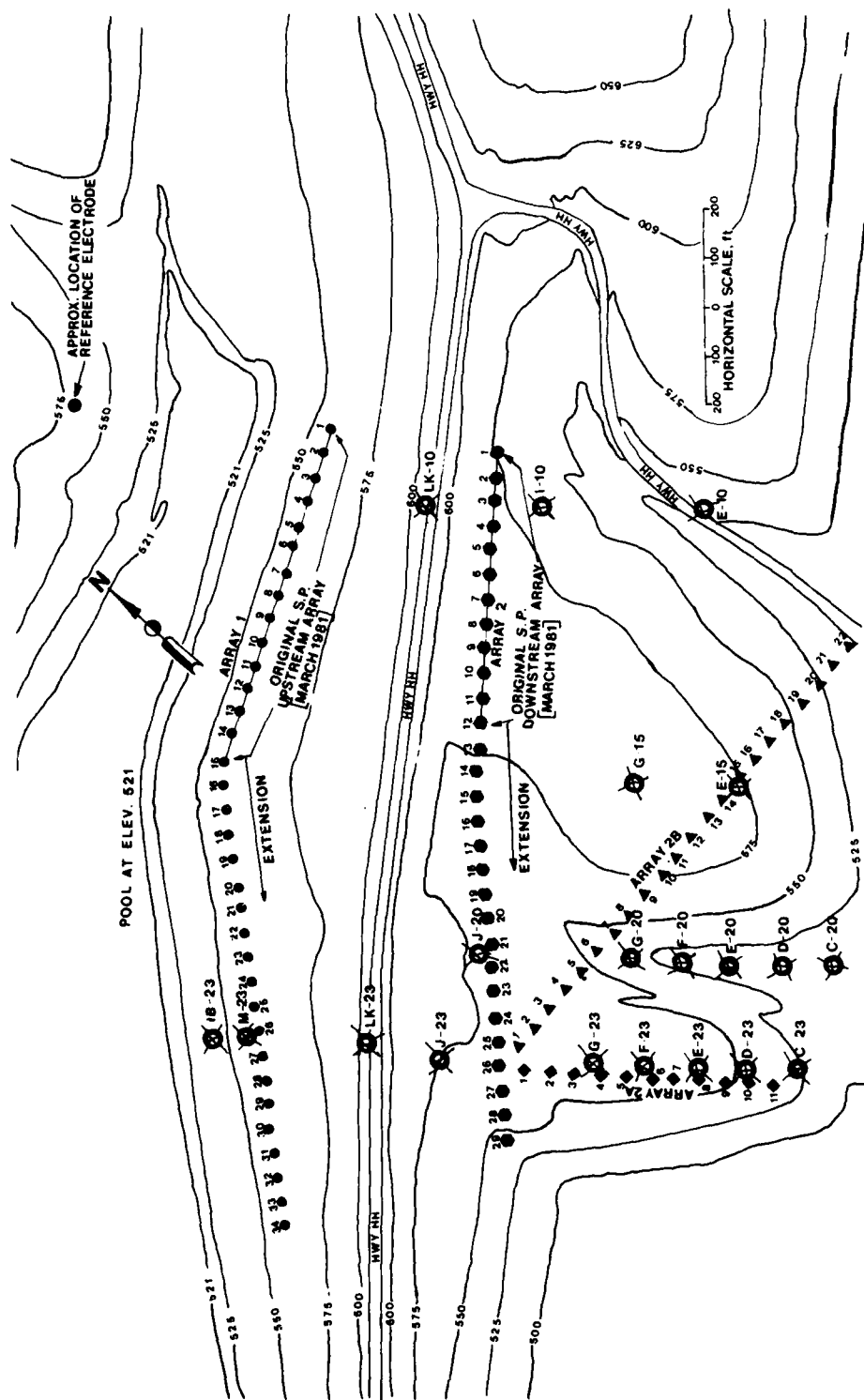
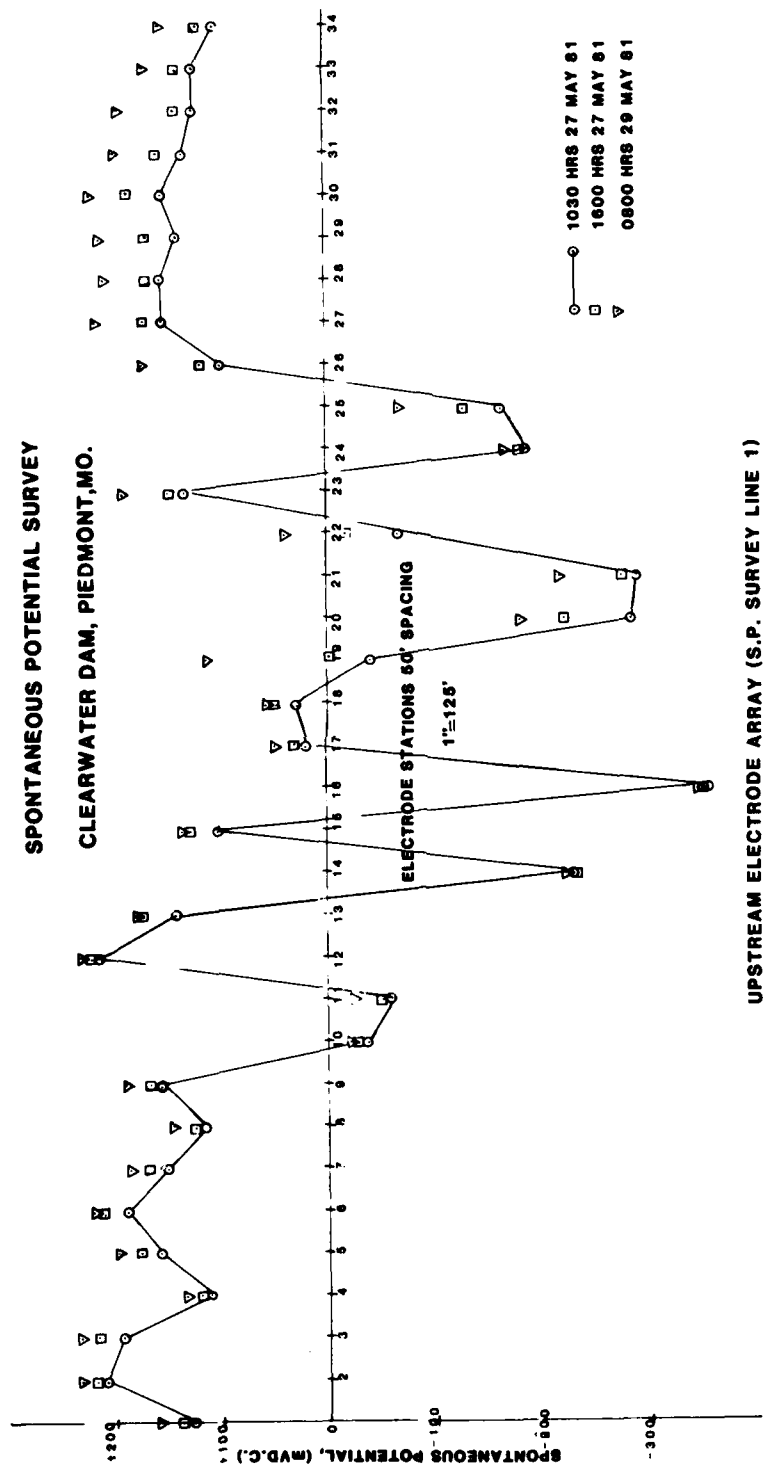Figure 29. Spontaneous-potential electrode locations

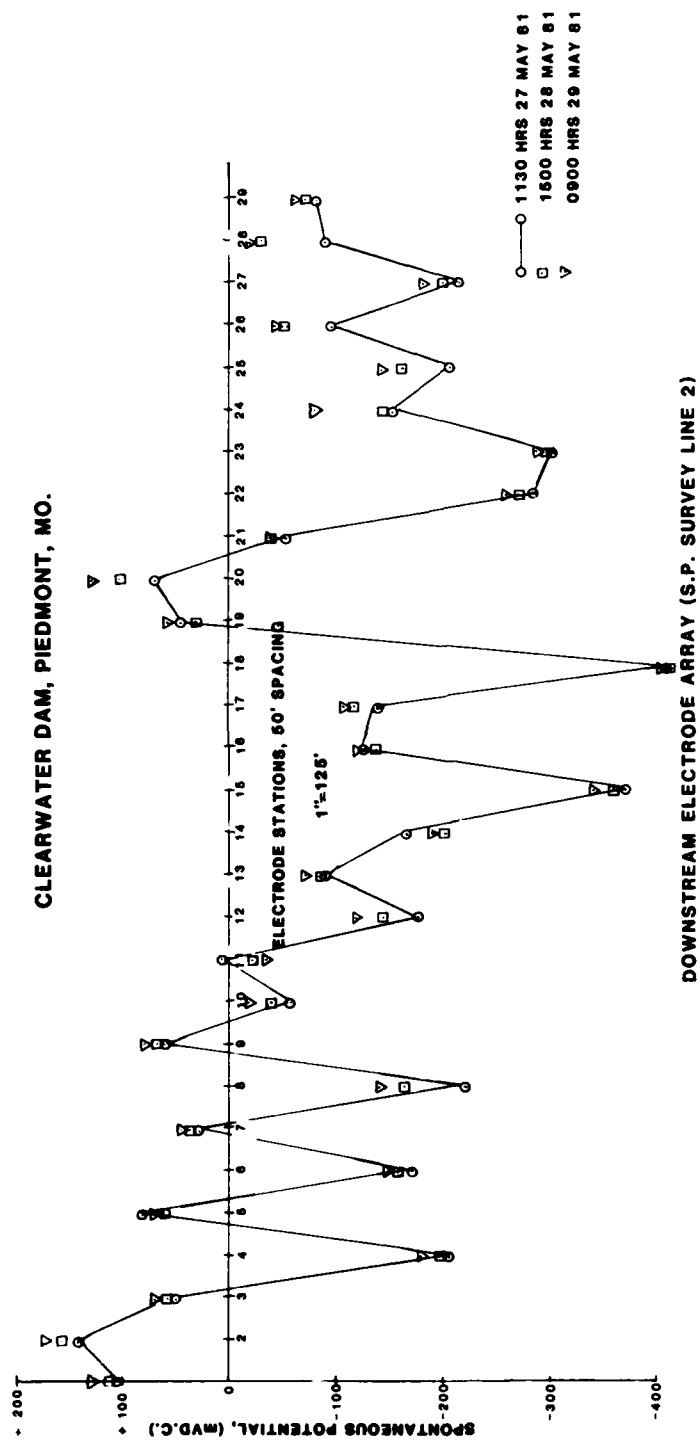Figure 30. SP survey results, array 1
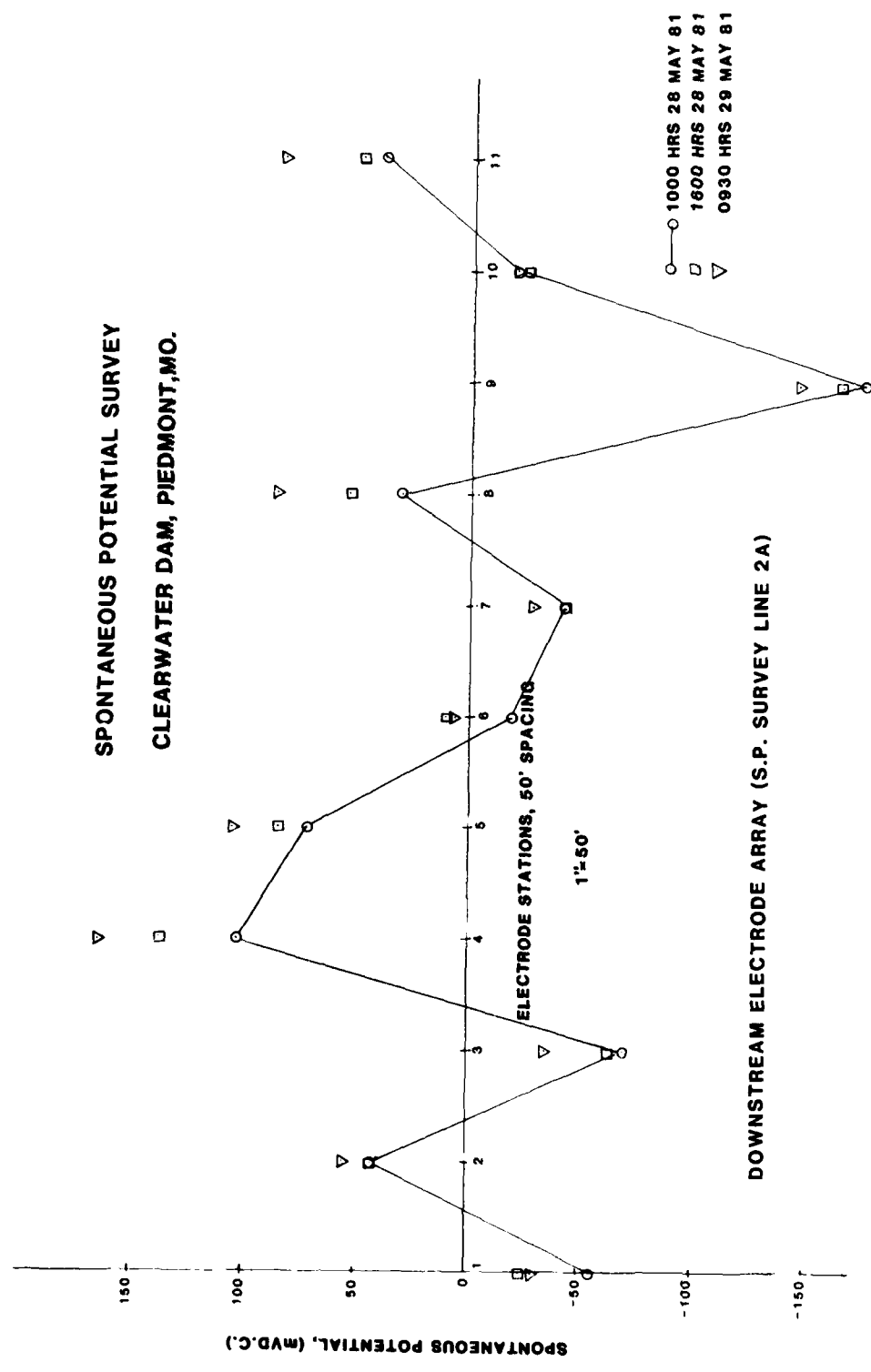
Figure 31. SP survey results, array 2

Figure 32. SP survey results, array 2A
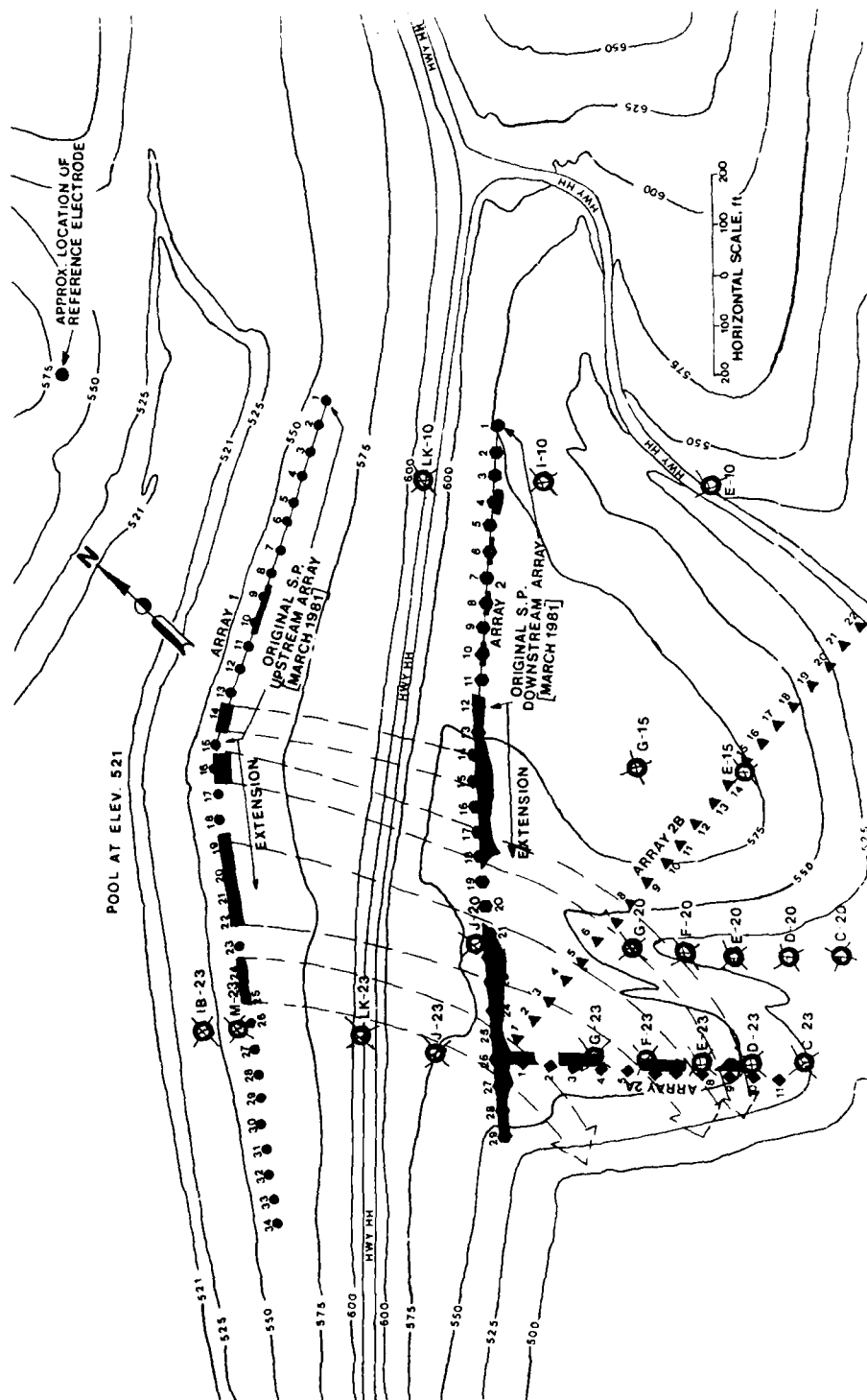
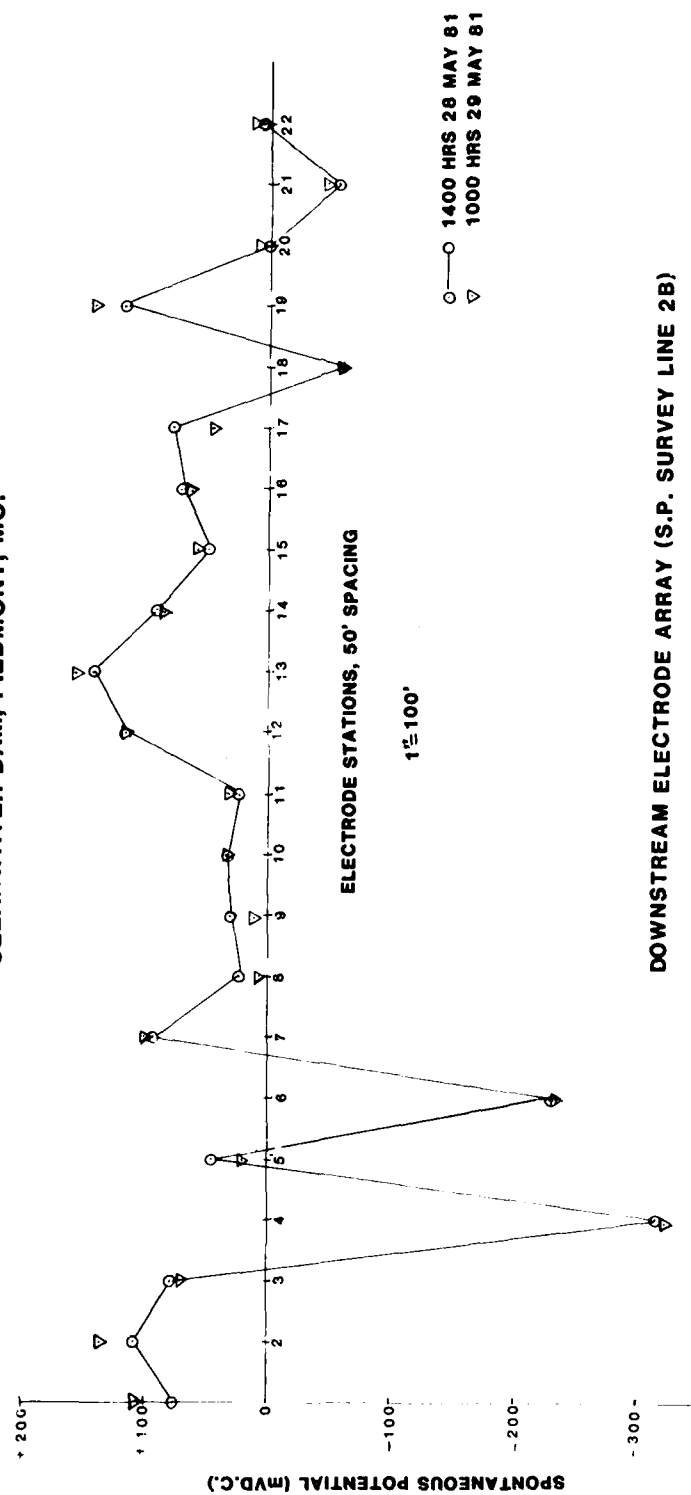Figure 33. Preliminary interpretation of results, arrays 1, 2, and 2A

SPONTANEOUS POTENTIAL SURVEY

CLEARWATER DAM, PIEDMONT, MO.

○——○ 1400 HRS 28 MAY 81
▷   1000 HRS 29 MAY 81

ELECTRODE STATIONS, 50' SPACING

1" = 100'

DOWNSTREAM ELECTRODE ARRAY (S.P. SURVEY LINE 2B)

SPONTANEOUS POTENTIAL (mVD.C.)

Figure 34. SP survey results, array 2B
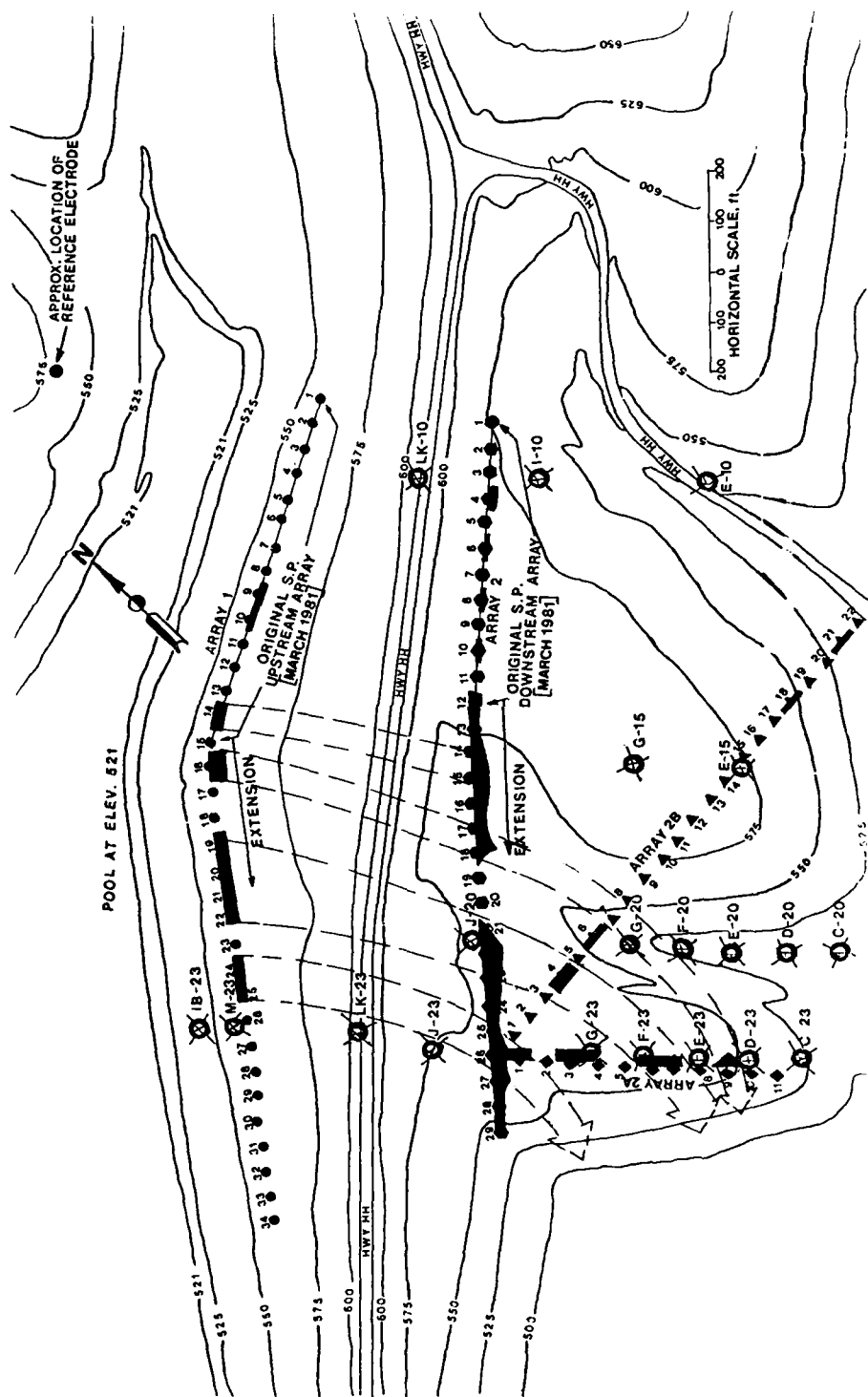
Figure 35. Confirmation of preliminary interpretation with array 2B

A. UPSTREAM S.P. ARRAY (SURVEY LINE 1, STA.1–15)
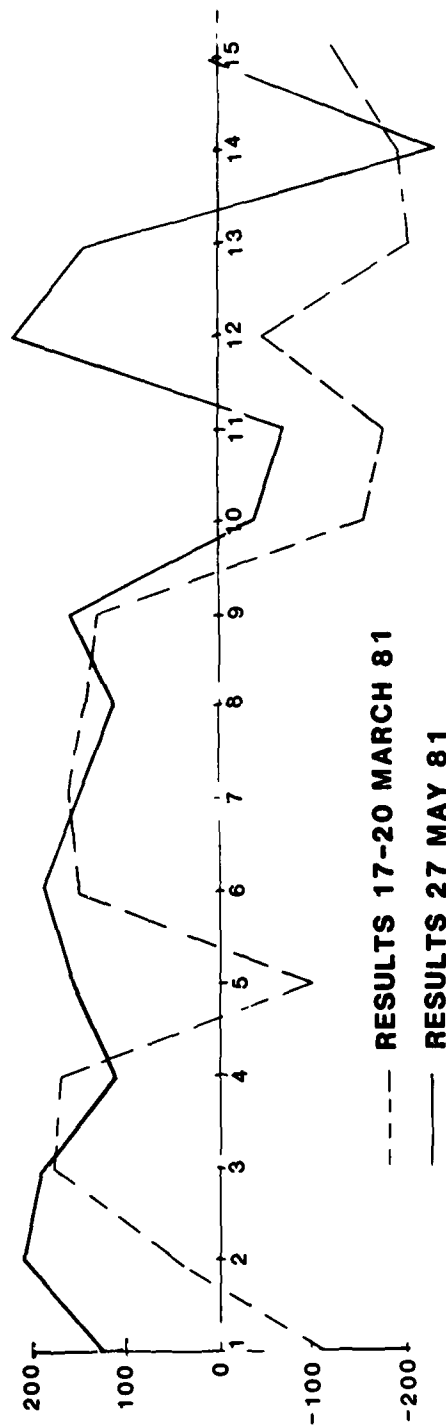
B. DOWNSTREAM S.P. ARRAY (SURVEY LINE 2, STA.1–11)

- - - RESULTS 17–20 MARCH 81
——— RESULTS 27 MAY 81
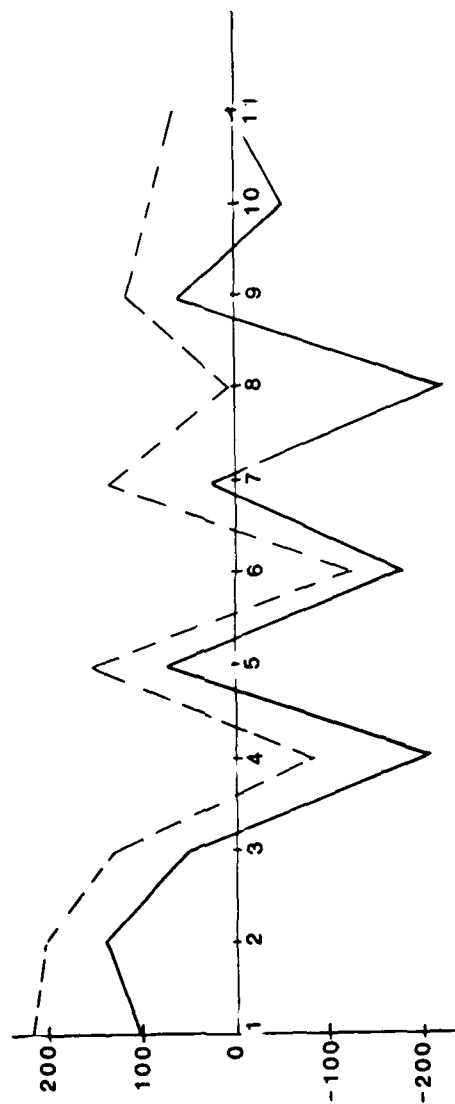
Figure 36. Superposition of March and May SP survey results

Figure 37. SP survey results, May-June, array 1

Figure 38. SP survey results, May-June, array 2

Figure 39. SP survey results, May-June, array 2A

Figure 40. SP survey results, May-June, array 2B

APPENDIX A

SEEPAGE DATA ANALYSIS AND SUMMARY

FROM
"Clearwater Dam Comprehensive Seepage
Analysis and Report, 1949 to 1981"

August 1981
by
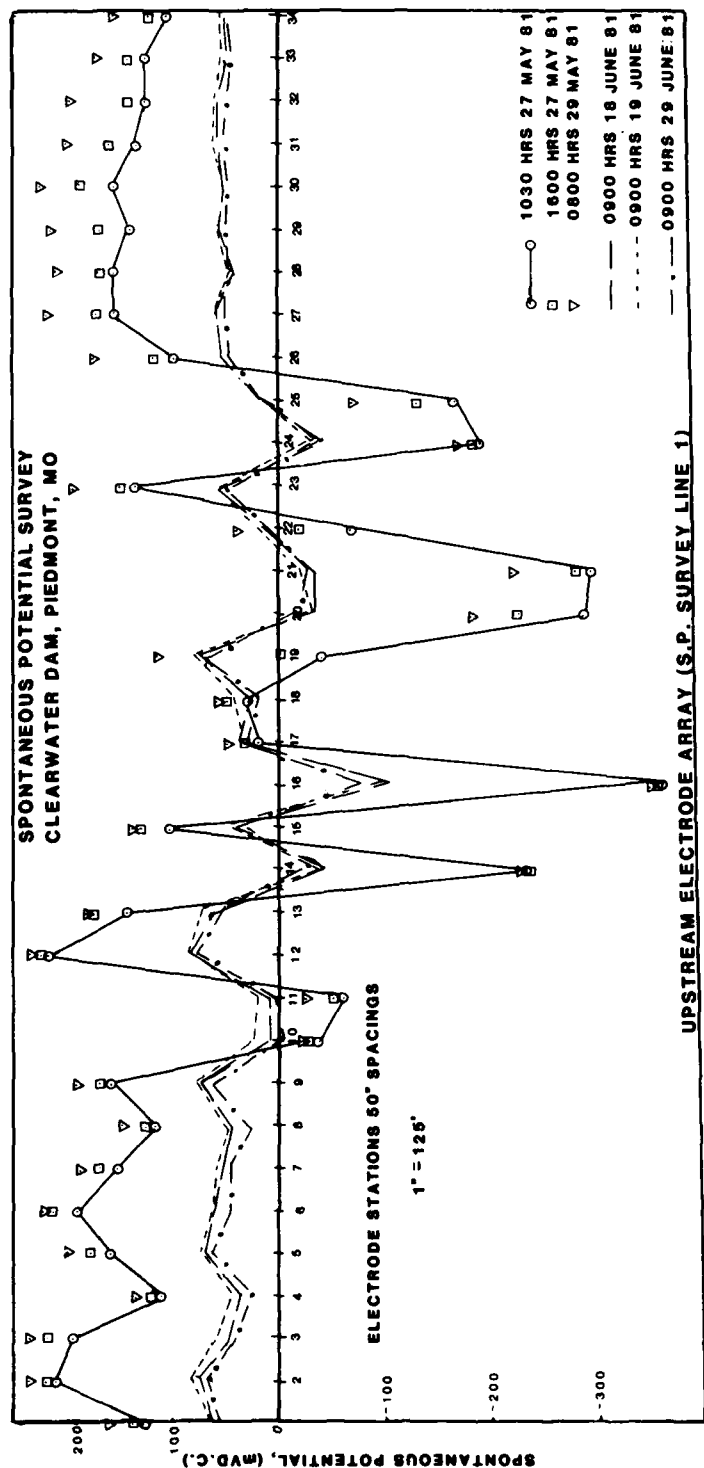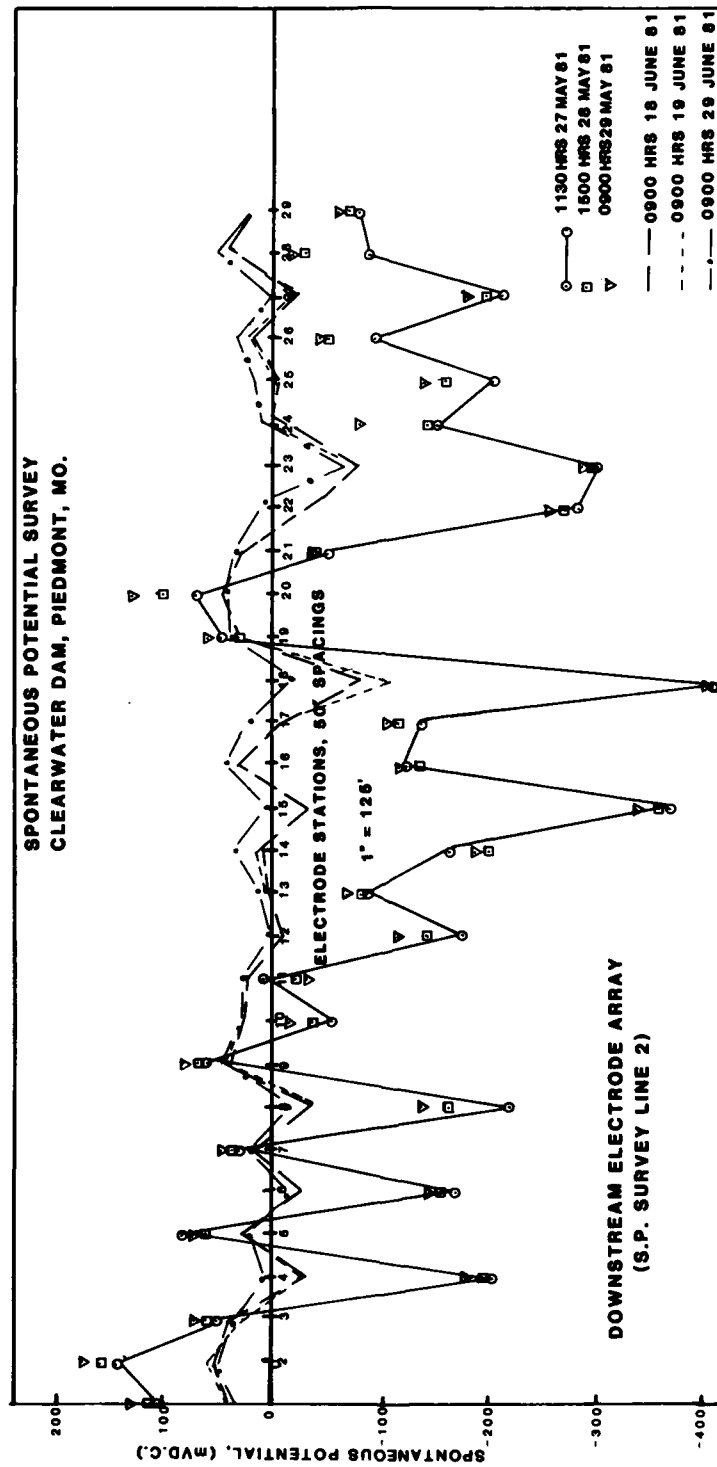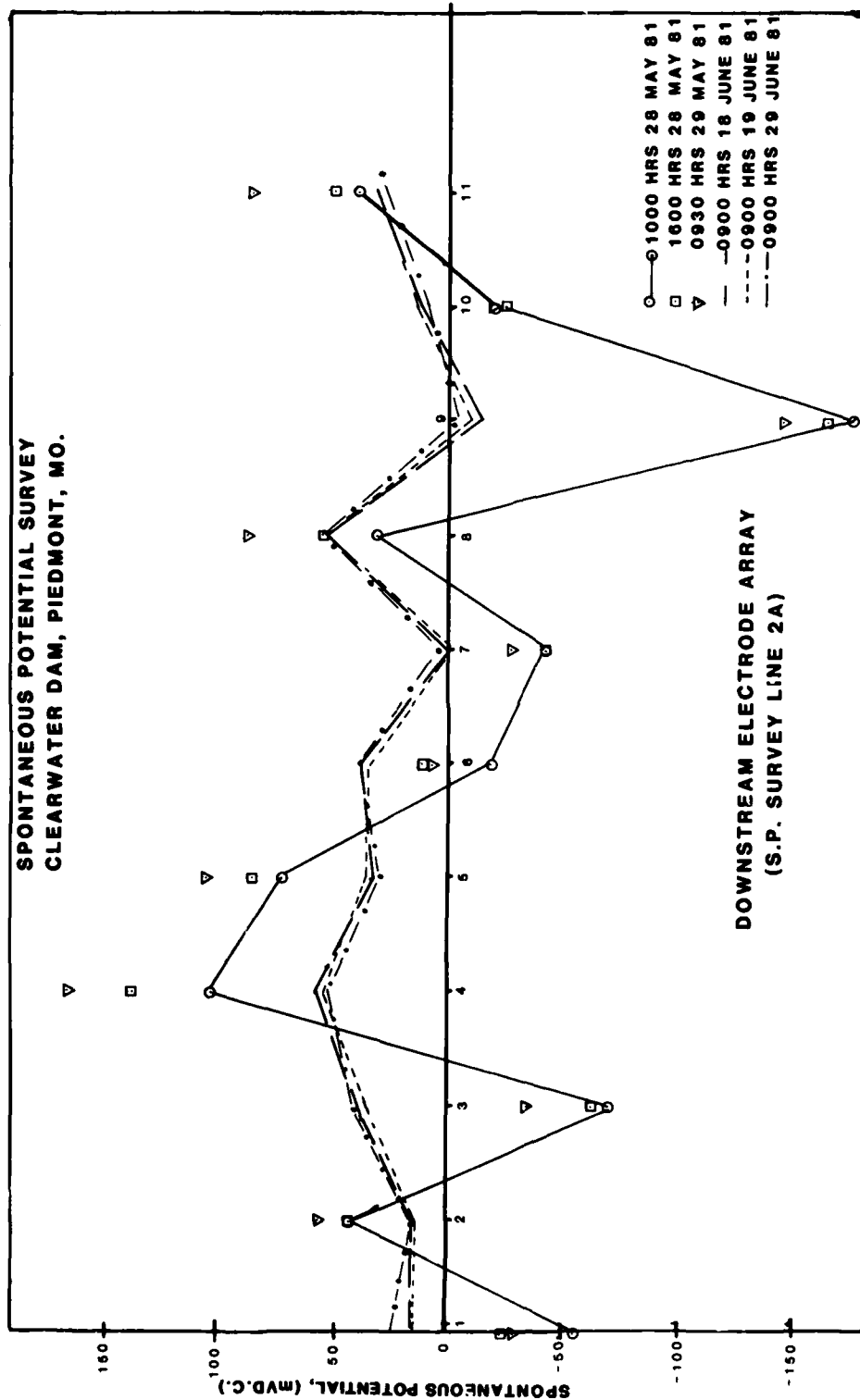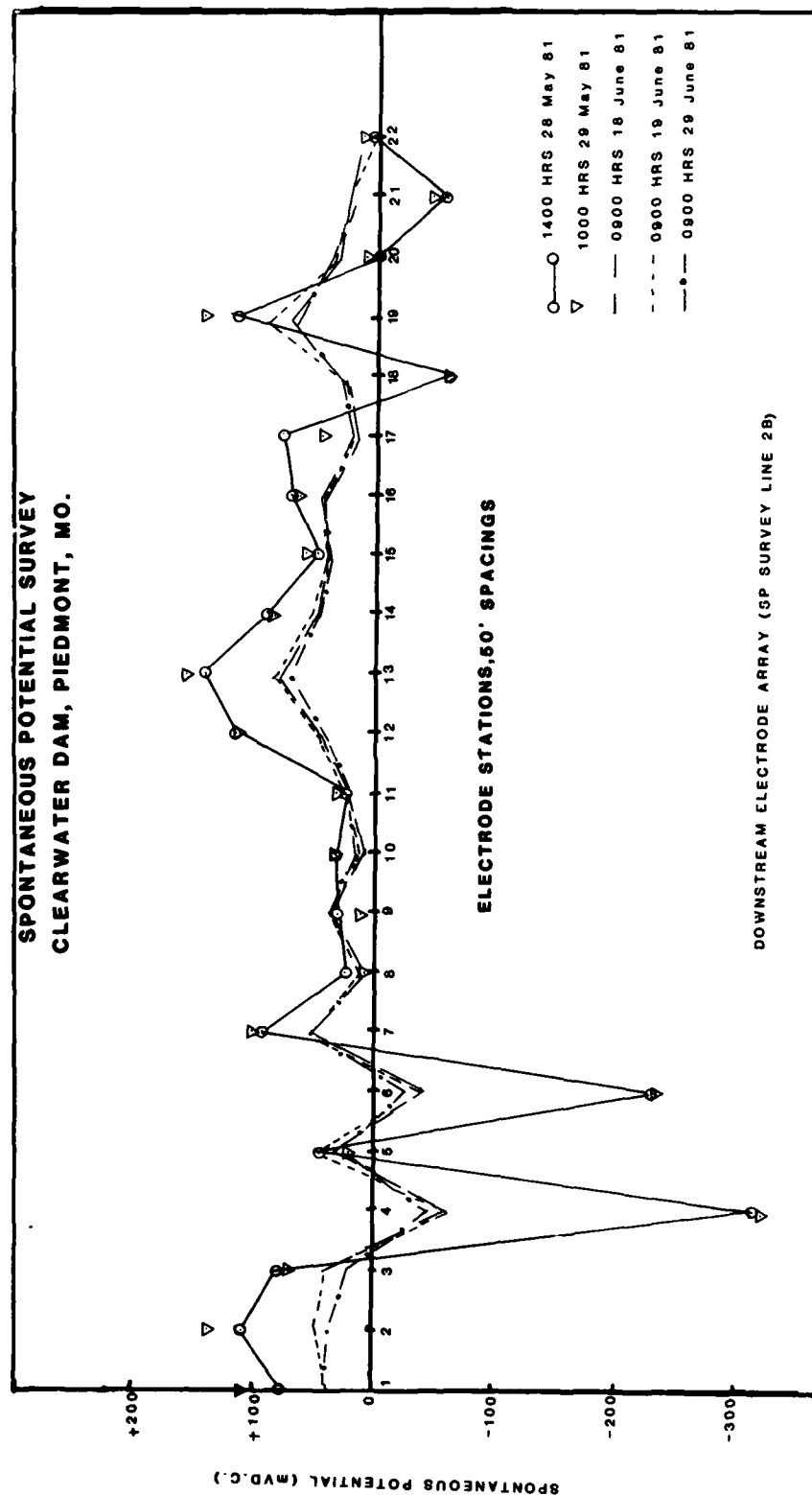U.S. Army Engineer District, Little Rock
Little Rock, Arkansas

APPENDIX A: SEEPAGE DATA ANALYSIS AND SUMMARY

Geological and Geophysical Analysis

1. From a summary of geological conditions at Clearwater Dam, which emphasize the "leaky" nature of the rock, a combined analysis of the geological and geophysical investigations will be made to identify probable areas (or paths) in the left abutment through which water (seepage) escapes from the reservoir.

Site Geology and Seepage

2. From the drilling of the first exploratory boring in the early 1930's to the present time, the rock foundation at Clearwater Dam has been a perplexing feature, and has affected all phases of the dam, from design and construction to maintenance.

3. Local Rock Formations. The highly jointed and fractured structure of both the Potosi and overlying Eminence Dolomites has resulted in weathering agents creating characteristics and features which, in combination, serve as ready outlets for water originating from both infiltration (rainfall) and the reservoir (seepage). Some of these characteristics are listed below:

Eminence	Potosi
Cherty and highly fractured.	Many subsurface water channels.
Solutioned at contact with Potosi.	Contains caverns and springs.
Weathers into pinnacles along joints.	Intensely fractured.
Springs/subsurface drainage is well developed.	Solution channels are extensive.

4. Joints in both formations strike from N50°E to N40°W, dip from near vertical to 70°, and are very closely spaced, from 2 to 6 inches. Chemical weathering along joint surfaces is pronounced and quite severe, especially in the abutments, forming solution fissures and cavities. The ultimate results of this corrosive

weathering are in some cases surface depressions, or sinkholes, which are common topographic features in this karstic area. Two large sinkholes were encountered during construction of the outlet works tunnel.

5. Porosity of Rock/Soil Transition Zone and Rock Cavities. In the abutments, the upper surface contact of the Eminence Dolomite with the residual overburden (soil) is an extensive, intensely weathered zone which has been labeled "Transition", or "B" zone. During drilling through this zone, total drill fluid (mud or water) loss is common. It is generally classified as a clayey sand, and is typically described as either saturated, very porous, highly pervious, or very soft. Drill bits and rods commonly drop or fall when this zone is encountered.

6. An example of the porosity of this zone in the left abutment is the "upper cavity" zone (el. 510±) encountered in boring LK10, where two pump tests were performed in February and March 1981. During the pumping phase into this "transition" zone (18-20 Feb), approximately two million (2,000,000) gallons of water were pumped. The porosity of the lower Potosi/Eminence rock contact is also exemplified by the pump test in boring LK10, in the "lower cavity" zone (el. 476±). Approximately 1.9 million gallons were pumped into this zone.

7. Conclusions. The deletion of full rock foundation treatment (grout curtain) in the left abutment has resulted in a constant, high head seepage flow through the rock in this abutment. The pressure head decreases during low (conservation) reservoir levels, which in turn decreases flow rate, but leakage is, and has been, constant and accelerated (exceeding pre-dam conditions) through the rock in this abutment.

8. The rock in the left abutment was in an advanced karstic stage of corrosion, channeling, cavities, etc., at the time the dam was constructed (1940's), as

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attested by the geological findings, test grouting results, and precautionary posture of the design/consultant group about this abutment.

9. The results of increasing the amount and flow of atmospheric[1] (reservoir) water through the dolomite rock in the left abutment beyond pre-reservoir conditions will be a proportionate decrease in the time required for the karstic features (cavities, etc.) to enlarge. This will conceivably hasten the possibilities of surface depressions (sinkholes) in this abutment.[2]

Geophysical Surveys and Seepage

10. Results of the borehole geophysical logs substantiate the widespread porous (open) condition of the rock beneath Clearwater Dam. Positive results were also obtained from geophysical surveys performed and reported by Waterways Experiment Station, Vicksburg, Mississippi. Many anomalous (potential seepage) areas are detailed in their report. With benefit of other complementary investigations and field tests, they become more significant, even to the possibility of identifying flow (seepage) paths. Analysis of these surveys in the left abutment are given below.

11. Phase I Surveys During Pump Test at Boring LK10 (March 17-20, 1981). A composite of key points (anomalies) from the geophysical surveys, and piezometers where water levels raised during the induced seepage pumping into boring LK10 are shown in Figure 1. The single-source seepage point

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[1]E. E. Wahlstrom, "Tunneling in Rock", 1973, Elsevier Scientific Publ. Co., pg. 119, " . . . carbon dioxide (from atmosphere) in ground water spectac-ularly increases its capacity to dissolve limestone."

[2]T. J. Aley, J. H. Williams, J. W. Massello, "Groundwater Contamination and Sinkhole Collapse Induced by Leaky Im, ndments", 1972, Missouri Geological Survey and Water Resources.

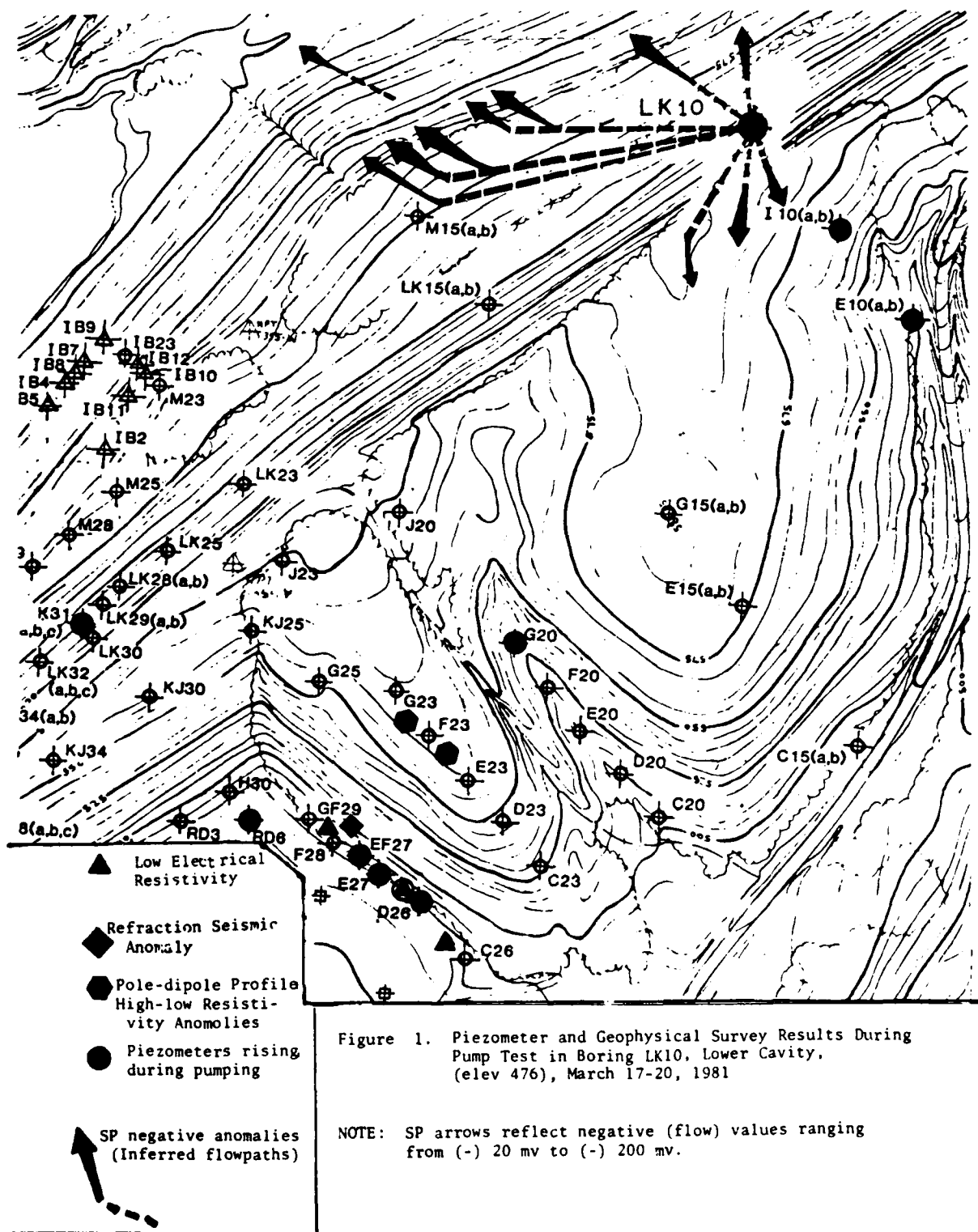Figure 1. Piezometer and Geophysical Survey Results During Pump Test in Boring LK10, Lower Cavity, (elev 476), March 17-20, 1981

NOTE: SP arrows reflect negative (flow) values ranging from (-) 20 mv to (-) 200 mv.

Legend:

▲ Low Electrical Resistivity

◆ Refraction Seismic Anomaly

⬢ Pole-dipole Profile High-low Resistivity Anomolies

● Piezometers rising during pumping

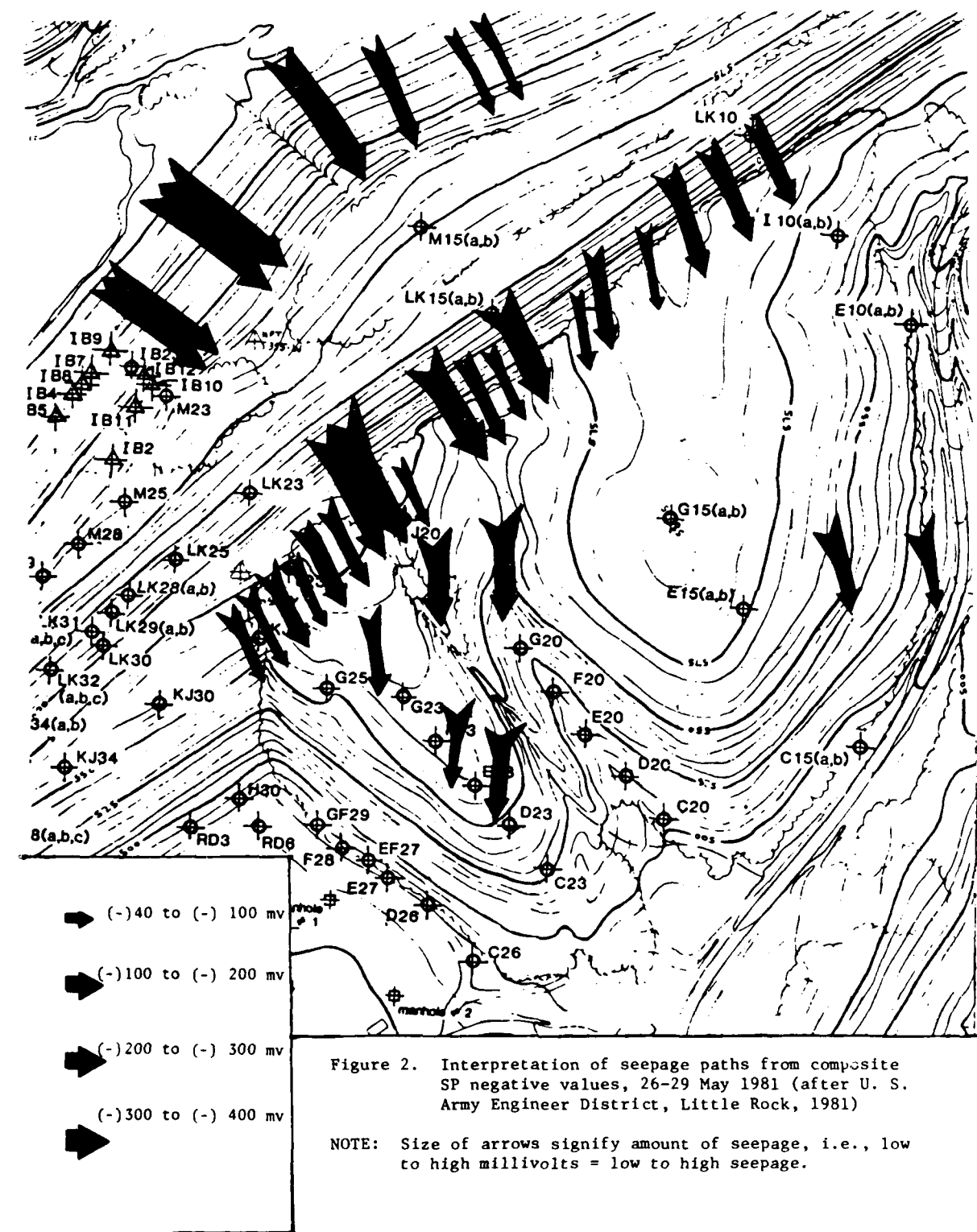SP negative anomalies (Inferred flowpaths)

(boring LK10) simulated in a very small but adequate way what occurs during high pool seepage periods. This is borne out alone by rises in piezometers D-26 and E-27 which have been the "centerpiece" piezometers where high pool seepage has surfaced through the years at the downstream toe of the left abutment.

12. WES reported that the results of the spontaneous (SP) surveys taken during this pump test were preliminary indicators of the feasibility of using this geophysical method for locating seepage zones. However in order to substantiate the results of these (Phase 1) surveys, the following requirements were made: (a) another SP survey should be taken during a high (flood) pool, (b) the existing survey lines should be extended toward the dam, and (c) other SP lines should be installed across other suspect seepage flow areas downstream of existing lines. During the high pool period of 26-29 May 1981, another SP survey was performed by WES in accordance with the above criteria.

13. Analysis of Extended SP Survey (Phase II) During High Pool (26-29 May 1981). The composite interpretation by WES personnel of the results of this survey becomes very significant when it is complemented with data and results of the other seepage investigations and tests, which will be shown in the final analyses and conclusions. Another interpretation of this survey is shown in Figure 2. The points of the arrows are all located at electrodes in the survey line that recorded negative voltage (suspect seepage flow) areas. The arrows are proportioned according to the recorded negative value; i.e., largest arrow electrode recorded (-)420mv (large flow) and smallest arrows recorded (-)40 to (-)60mv (smaller flow). The credence of both this survey and the earlier SP survey are further enhanced when negative arrows are matched upstream and downstream of boring LK10; i.e., the same electrodes (arrows) are significantly negative in

Figure 2. Interpretation of seepage paths from composite SP negative values, 26-29 May 1981 (after U. S. Army Engineer District, Little Rock, 1981)

NOTE: Size of arrows signify amount of seepage, i.e., low to high millivolts = low to high seepage.

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both surveys (Figures 1 and 2).

14. Negative values continued at the larger flows (arrows) as the reservoir descended in June, which confirms other data that seepage continues in rock as the pool descends. Most of the large flows (arrows) shown in Figure 2 continued to have negative values (from -50 to -150mv) at lower pools, indicating that uninhibited flow through the rock of the left abutment continues even during low (conservation) pools.

15. Conclusions. Negative values recorded during the spontaneous potential surveys show apparent flow (path) of water during both the simulated (pump test) and high pool conditions. When compared with other seepage tests and investigations, these surveys become very significant in determining seepage paths. The electrical resistivity and refraction seismic surveys provided additional information that cavities, voids, and channels are quite extensive in the rock, and they also provided locations and depths of some of these features.

Seepage Flow and Path Analysis

16. Seepage Flows. Pumping test results show that subsurface water flows are for the most part free and uninhibited in rock beneath the left abutment, particularly at the transition "B" zone contact between the upper Eminence Dolomite and soil overburden; and also in the area at the contact between the Eminence and underlying Potosi Dolomite. The pump tests also indicate free flow capability through interconnecting joints, fractures, cavities, and solution channels between the pumping site (Boring LK10) and other piezometers.

17. Chemical dye tracing tests also indicate that there are many and varied subsurface connections between piezometers, both beneath the dam and left abutment.

18. Piezometric data flow analysis shows that seepage through the rock

foundation under the dam is present at all pool levels and the quantity of seepage increases with increased pool levels. This is substantiated by spontaneous potential (SP) geophysical surveys, which showed greater to lesser (but continuous) negative (flow) values as the pool decreased.

19. Downstream of the grout curtain and impervious core trench beneath the earth embankment, piezometric heads are rapidly transmitted and dissipated through the alluvial soils, and piezometer levels closely follow tailwater levels.

20. Spontaneous Potential (SP) geophysical surveys conducted during both simulated (pumping) seepage and flood pool seepage conditions provided significant data showing apparent seepage flows through a major section of the left abutment.

21. Perched water tables can occur from heavy rainfall saturating the soil and infiltrating to and raising levels of piezometers prior to rises in reservoir pools.

22. Piezometric level contours through the left abutment during normal (low) pools are on an even, gradual, widely sweeping slope; whereas during high pools these contours become irregular and undulating (nosing), indicating volumetric (low and high) flow trends toward the downstream valley. The latter trends complement and substantiate results of the SP surveys conducted by Waterways Experiment Station.

23. Seepage Paths. It is possible to infer or imply directions (or paths) of seepage from any given method of investigation or testing performed at Clearwater Dam. However, in the total analysis certain investigative methods show a greater degree of inference than others, namely the spontaneous potential (SP) survey and consistent high levels (potentiometric surfaces) in

certain piezometers during higher reservoir levels.

24. Plotting of results of both the SP survey (particularly Phase II) and piezometric highs during high reservoir levels are reasonably coincidental, insofar as general trends. This correlation between the two methods gives credence to designating the results as seepage paths. Taken individually, however, without benefit of verification from other information, it would be difficult to designate (or conclude) the results as seepage paths.

25. The spontaneous potential (SP) survey results (Figure 2) also provided orders of magnitude for each negative (seepage) anomaly, which appeared to vary in proportion to suspected flow quantities (higher reservoir level = greater seepage flow = higher negative values (anomalies)).

26. Conclusions. (Note: Only conclusive points made relating to results of the WES investigation are given below. Full conclusions are given in U. S. Army Engineer District, Little Rock (1981).)

27. Leakage (seepage) occurs through the rock in the left abutment from the reservoir (upper pool) during both flood pool conditions and conservation pool conditions.

28. Seepage which has been suspected as occurring through the so-called "window" area between the left abutment end of the impervious core/grout curtain junction and the impervious clay blanket has been confirmed as an area of excessive (high) piezometric levels and convergence of equipotential flow curves, at least during high flood pools. It is important to note, however, that seepage is occurring through the entire left abutment.

29. Seepage flows from the reservoir through the rock in this abutment are constant. Flow rates and pressures, however, increase as upper pools increase (rise). These findings were a consensus opinion from all of the 1980-81 independent studies; i.e., piezometric, geological and geophysical,

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and which are elaborated as follows:

30. Piezometric water level contours during normal (conservation) pools have gradual, widely sweeping, downward slopes; whereas during high pools the contours become locally steep, irregular, and undulating (nosing). The latter contour trends are indicative of volumetric (high and low) flow trends (paths) toward the downstream valley.

31. Water pumping and dye tracing tests in this abutment indicate that the interconnecting karstic channels and cavities will allow very high flow rates. Numerous open subsurface connections at various elevations were indicated from these tests.

32. Spontaneous potential (SP) geophysical surveys show that flow rates throughout this abutment greatly increase as the upper pool rises. These surveys also inferred consistent flow paths during both high and low pools

33. Although there has been no apparent piping and/or flushing of fine soils from the left abutment, nor from the main embankment near this abutment, a potential risk or danger of sinkholes exists. As indicated in the geological conclusions the karstic weathering was already in an advanced stage in this abutment during design and construction in the 1940's. Further, it was concluded that the increased quantities and pressures of water flows (over pre-reservoir conditions) through this rock will result in a proportionate decrease in the time required for the karstic features (cavities, etc.) to enlarge, which is a proven result of carbon dioxide fed (reservoir) water on dolomite. This will conceivably hasten the possibilities of surface subsidence in this abutment. These phenomena (sinkholes) can be typically non-predictable and occur suddenly, or predictable, whereby subsidence occurs over a long period.

Sudden collapses are not uncommon in this karstic area. In the reference cited in geologic conclusions Missouri Geological Survey[1] describes sinkhole formation and collapse caused by reservoir impoundments in southern Missouri.

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[1] Aley, Williams, and Massello, op. cit.

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